The CENER model: Cost-effective nutrient emission reduction (CENER of the load to the North Sea from the Rhine and Elbe basin

Lise, W.

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Cost-Effective Nutrient Emission Reduction (CENER) of the load to the North Sea from the Rhine and Elbe basin

Wietze Lise

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IVM

Institute for Environmental Studies
Faculty of Earth and Life Sciences
Vrije Universiteit
De Boelelaan 1087
1081 HV Amsterdam
The Netherlands

Tel. ++31-20-4449 555
Fax. ++31-20-4449 553
E-mail: info@ivm.falw.vu.nl

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Contents

Abstract

For sustaining the ecosystem of the North Sea, the inflow of the nitrogen (N) and phosphorus (P) needs to be reduced. The OSPAR agreement calls for a reduction of 50% N and P with respect to 1985 levels. A flat rate policy where nutrient reductions are the same for all sectors and regions, may lead to unnecessary high costs. The CENER (Cost-Effective Nutrient Emissions Reductions) model has been developed to find a regionally and sectorally differentiated cost-optimal solution.

The model distinguishes between measures and quota restrictions at 8 farm types and measures at wastewater treatment plants (WWTPs) in the Rhine and Elbe river basins. In the model, the Rhine basin is divided into 9 and the Elbe basin into 8 geographical regions, following the Water Framework Directive. Besides, there is also the option to retain nutrients through 'wetlands' in the model. The model assumes that only a fraction of the emitted nutrients are transported from the source to the Sea. This is represented by so-called transport coefficients, which are derived from GIS-based models. Cost abatement curves are estimated for agricultural sectors, wastewater treatment plants and wetlands. These costs are upscaled to the basin level from a detailed study on the Netherlands. Costs depend linearly on the number of animals, amount of land and number of inhabitants in the catchment and increase quadratically in the amount of reduction at the source. Finally, the model calculates how to reach a desired load to the Coastal Sea at lowest cost.

Calculations with the model indicate an annualised cost (with respect to 1992 prices) of 605 million euro for the Elbe basin without using wetlands and 604 million euro for the Elbe basin with using wetlands, 1138 million euro for the Rhine basin without using wetlands and 841 million euro for the Rhine basin with using wetlands. The outcome of the model suggests that it is cost effective to devote 4.0% of arable land to wetlands in the Rhine basin, while the model suggests only a conversion of 0.3% of arable land to wetlands in the Elbe basin. A possible explanation for this difference is that there is more arable land in the Elbe basin, while the numbers of animals and people are substantially lower in the Elbe basin.

1. Introduction

European catchment changes and their impacts on the coast (EUROCAT)[1] is an ongoing project commissioned by the General Directorate Research and Development (DG-XII) of the European Commission. In this project, we are developing a quantifiable framework of analysis for improved planning and management of catchments by analysing the response of the coastal sea to changes in fluxes of nutrients and contaminants from the catchments. The results of this study will be useful for developing better management solutions and strategies with regards to catchment sources of contamination and their coastal impacts, and in particular will assist managers in the implementation of the Water Framework Directive.

To protect the ecosystem of the North Sea, the North Sea conference and the OSPAR commission decided that emissions needs to be reduced from its main contributing rivers. This has resulted into policies being put in place restricting emissions of various substances, namely emissions of heavy metals should be reduced by 80%, while nutrients should be reduced by 50%. These strict emission requirements have led to a substantial decrease in the emissions of heavy metals to water. This did, however, not lead to the desired decrease in the total emissions of nutrients. While nutrient emissions from point source have been reduced by more than 50% through a large number of newly constructed wastewater treatment plants, nutrient emissions from diffuse sources fell only by about 10 to 20%. The total reduction of nutrients amounts to 20 to 30%, which is below the set standard. Thereupon, we focus on nutrients alone in this report.

One could argue that in order to reach a certain reduction in the load in a coastal sea, it is fair that each polluter has to reduce its emissions by the same fraction. This so-called flat-rate reduction target does not need to be the cheapest way to achieve a certain reduction in the load. River basins are, generally, situated in multiple countries, where the political, economical and geographical conditions can vary considerably. In the case of river basins, it may be substantially cheaper to follow regionally differentiated reduction targets. To derive such regionally differentiated reduction targets is, however, a complex issue, which can only be approached by the use of models. Thereupon, this report presents the optimisation model, which can calculate Cost-Effective Nutrient Emissions Reductions (the CENER model). The CENER model is formulated to find regionally differentiated reduction targets, such that the load to the sea is reduced at least cost. Furthermore, due to budget constraints of the EUROCAT project, we restrict ourselves to nutrient loads originating from the Rhine and Elbe rivers. These are the two biggest rivers streaming into the North Sea from the European mainland. Possibly the solutions proposed for the biggest rivers also hold for the smaller rivers of the Scheldt, Muese, Ems and Oder rivers. A map of the Rhine and Elbe catchment is given in Figure 1.1. Catchments generally do not respect political borders and may cover various countries and/or administrative regions. The water framework directive (WFD) divides the catchment into sub-catchments based on natural flow. For instance, the Rhine basin is divided into 9 regions and the Elbe basin is divided in 8 regions (see Figure 1.1).

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[1] http://www.iia-cnr.unical.it/EUROCAT/project.htm

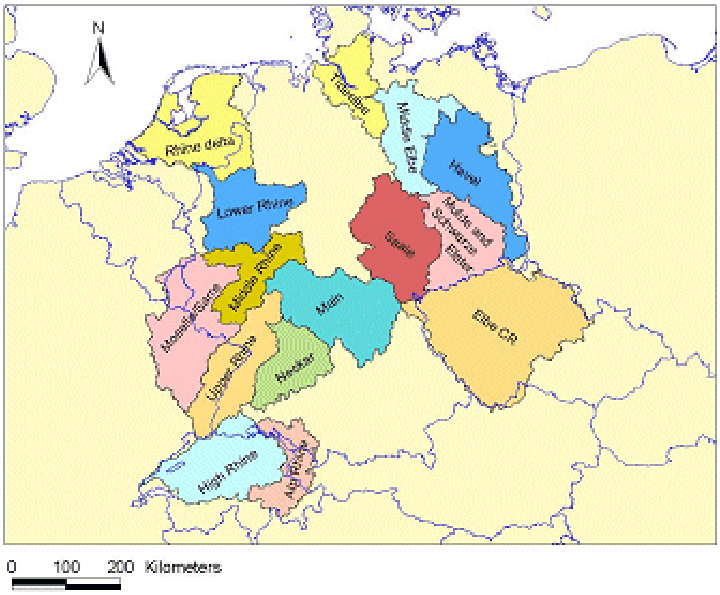


Figure 1.1 WFD division of the Rhine and Elbe catchment.

Source: IGB (2003).

Note: The Czech part of the Elbe, which is shown as one region in the picture (the best available to us), is divided into three WFD regions.

The primary objective of this report is to find a cost-effective allocation of nutrient abatement, by trading off sets of policy measures, which can target various pressures in the catchment. The main pressures are agriculture, wastewater and sewage treatment plants (covering both households and industry) and wetlands. Hence, the research question at hand is: what are the characteristics of a cost-effective solution for achieving a given target on nutrient loads? More specifically, we would like to find the sectoral distribution of reduction targets in the cost-optimal solution and the cost difference with the flat-rate reduction targets. Besides, we would like to shed light on the usefulness of wetland construction in reducing nutrients.

This study considers nutrient abatement options by agricultural sources and wastewater treatment plants only. These sources cover approximately 95% of nutrient emissions (RIVM, 2000).

The data required for modelling a cost effective nutrient emission reduction at the catchment level can be divided into five stages. An elegant way of such a division is by following the five stages of the Driver-Pressure-State-Impact-Response (DPSIR) framework (see Figure 1.2). In the catchment, four *drivers* are distinguished, namely animals, (agricultural) land, people and retention (through biological processes in the soil and wetlands). These drivers emit nitrogen including ammonia (N) and phosphorus (P) to the catchment: the *pressures*. Due to model restriction, we assume here that a fixed linear fraction of the emissions from animals, land and people ultimately reaches the sea: the transport coefficients. This is simplification of the reality, where a whole chain of chemical and biological processes proceeds between the time of emission and the time when this emission reaches the sea. From driver's emissions and the transport coefficients, the loads to the sea can be calculated: the *state*. It is generally argued that this nutrient load to the sea influences the risk of algae blooming and foam formation in the coast: the *impact*. Figure 1.2 shows the structure of the problem and the link with DPSIR.

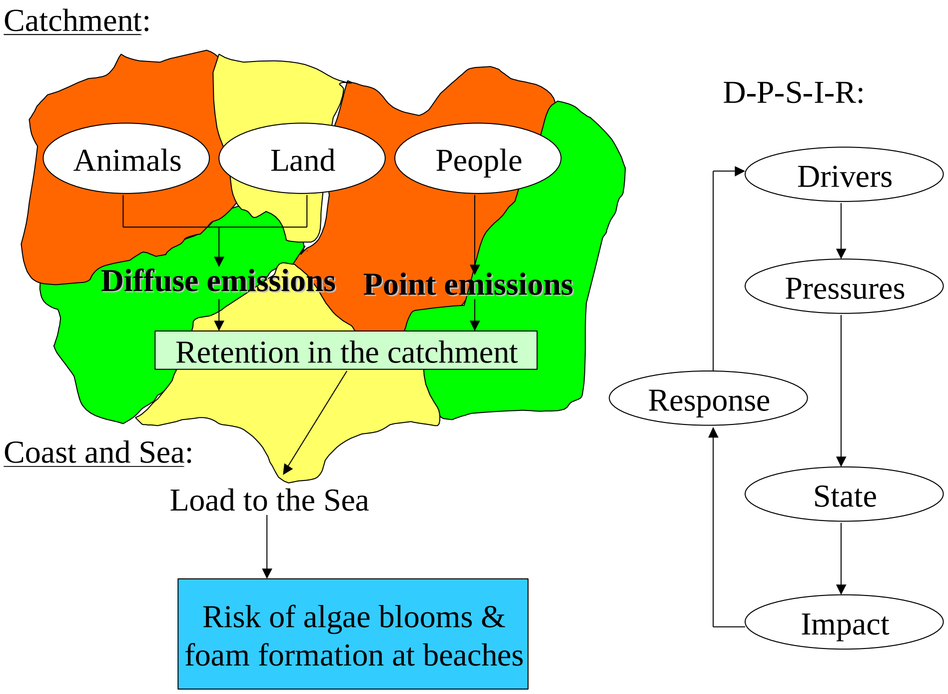


Figure 1.2 Catchment–coast interaction in the CENER model.

In order to reduce these negative impacts, a policy *response* is possible, at a certain cost. For calculating these costs, we need data on the cost of reducing emissions at farms or wastewater treatment or via increasing retention through wetlands.

The CENER model calculates the cost-effective joint N and P emission reduction in the Rhine and Elbe river basin, to achieve a desired load in the North Sea. It simultaneously considers diffuse emissions from farms and point emissions from wastewater treatment plants in the WFD regions and nutrient retention by wetlands. Besides a differentiation between N and P in the model, a further differentiation is made between measures and quota restrictions to reduce diffuse nutrient emissions.

The outline of this report is as follows. Chapter 2 presents the data describing the current level of emissions in the river catchment, which originate from animals, land and people, and the resulting load into the sea. Chapter 3 presents the data on costs and effects of policy measures to reduce nutrients. Furthermore, cost abatement curves are derived for measures to reduce nutrients at farms, wastewater treatment plants and wetlands. This information is used in Chapter 4 for estimating the marginal cost of changing the input and retention of nutrients in the river catchment. The data, as described in Chapter 2–4, is used to calibrate the CENER model, of which the mathematical structure is presented and explained in Chapter 5. The results, which can be achieved with the CENER model, are presented in Chapter 6. The CENER model is run four times, namely a 50% N and P load reduction in the Elbe and Rhine river basin, where the option to increase retention via wetlands is either included or excluded. Section 6 also interprets the outcome and discusses the reliability of the calculated regionally differentiated reduction targets by the CENER model. Chapter 7 concludes.

2. Data on emissions and its transport to the sea

2.1 Drivers – animals, land, people

In going through the DPSIR representation of nutrient emissions from the catchment to the sea, as shown in Figure 1.2, we have identified the drivers in the catchment: animals, land and people. The total numbers determine their impact. More specifically, we distinguish between four kinds of animals: the total numbers of poultry, dairy cows, breeding and feeding pigs; hectares of arable land; and the number of people measured as inhabitant equivalents (IEs) per subcatchment.

Table 2.1 Numbers of poultry, arable land (hectares), cows, breeding and fattening pigs and inhabitant equivalents in the Elbe basin.

numbers (x1000)	Poultry	Dairy cows	Breeding pigs	Feeding pigs	Arable land [ha]	Inhabitant equivalents
1. Oberelbe	8422	169	94	425	784	2658
2. Vlatava/Moldau	15973	321	179	805	1598	5041
3. Ohre/Eger	4647	93	52	234	523	1467
4. Saale	472	221	130	373	1583	6674
5.Mulde-Schwarze Elster	314	201	88	207	1047	5270
6. Havel	2689	154	69	155	949	8240
7. Middle Elbe	1782	169	78	229	962	2022
8. Tideelbe	1834	283	80	393	584	5527
SUM	36132	1612	770	2822	8030	36898

Source: IGB (2003).
Note: The number of Inhabitant Equivalents (IEs) is equal to the regional population times 1.5.

The 8 subcatchments in Table 2.1 are numbered from upstream (Czech Republic) to downstream (Tideelbe). Table 2.1 shows that the largest amount of arable land is found in the region Vlatava/Moldau in the Czech Republic and the region Saale in Germany. In Vlatava/Moldau the number of animals as measured by the number of poultry, dairy cows and pigs is also the highest. Hence, Vlatava/Moldau contains the biggest land and animal pressure in the Elbe catchment. The region Havel of Germany, which contains the city of Berlin, has the biggest human pressure in the Elbe catchment, as it is the most populated region.

The numbers for the Rhine are available from Van der Veeren (2002, table 3.12), but at a different scale. In that study, the catchment is divided into 13 regions based on 7 country-borders, where Germany is further divided into 7 administrative regions or länder. These numbers are converted into the 9 WFD regions by using Table 2.2, which contains the area equivalence between the political division into 13 regions and the WFD division into 9 regions. We realise this conversion in three steps. First, we divide the values in the rows of Table 2.2 by their totals. Second, we multiply these fractions with the numbers from Van der Veeren (2002, table 3.12). Third, we add these numbers over the columns into the WFD regions. This method has been applied to derive the number of animals and inhabitant equivalents in Table 2.3. The amount of arable land is obtained directly from IGB (2003).

Table 2.2 Correspondence of region size between 13 political and 9 WFD regions.

	[km^2]	Alp Rhine	High Rhine	Mosell e/Sarre	Upper Rhine	Neckar	Main	Middle Rhine	Lower Rhine	Rhine Delta	total
1	Switzerland & Liechtenstein	5572	21883	0	76	0	0	0	0	0	27531
2	Austria	2355	0	0	0	0	0	0	0	0	2355
3	France	0	122	15325	8148	0	0	0	0	0	23595
4	Luxembourg	0	0	2511	0	0	0	0	0	0	2511
5	Belgium	0	0	769	0	0	0	0	0	0	769
	Germany:										
6	Thuringen	0	0	0	0	0	854	0	0	0	854
7	Nordrhein-Westfalen	0	0	91	0	0	0	406	18101	2194	20791
8	Hessen	0	0	0	1459	284	5082	5262	7	0	12093
9	Rheinland-Pfalz	0	0	6980	3553	0	0	8485	778	0	19796
10	Baden-Wurttemberg	2808	2211	0	7557	13628	1646	0	0	0	27851
11	Saarland	0	0	2457	0	0	0	112	0	0	2569
12	Bayern	575	0	0	0	17	19658	0	0	0	20250
13	The Netherlands	0	0	0	0	0	0	0	119	21812	21931
	total	11310	24216	28132	20794	13929	27240	14266	19005	24006	182897

Source: IGB (2003).

Table 2.2 provides a means to convert data from the country level to the WFD subcatchment division. Table 2.2 also gives the country/länder composition of the WFD subcatchments in area equivalents. For instance, 90% of the area of the Rhine delta is located in the Netherlands and 10% in the German region of Nordrhein-Westfalen.

The 9 subcatchments in Table 2.3 are numbered, as before, from upstream (Switzerland) to downstream (the Netherlands). Table 2.3 shows that the largest amount of arable land is found in the region Main of Germany. The biggest animal pressure is found in the Rhine Delta, with 66% poultry, 30% dairy cows and 32% pigs of the total numbers in the Rhine catchment. The region Lower Rhine in Germany, which contains the industrial Ruhr area, is the most populated subcatchment and has the highest animal pressure.

Table 2.3 Numbers of poultry, arable land (hectares), cows, breeding and fattening pigs and inhabitant equivalents in the Rhine basin.

numbers (x1000)	Poultry	Dairy cows	Breeding pigs	Feeding pigs	Arable land [ha]	Inhabitant equivalents
1. Alp Rhine	2753	399	122	332	155	5219
2. High Rhine	3873	529	153	451	473	5579
3. Moselle/Sarre	2078	413	54	140	1086	6432
4. Upper Rhine	2050	332	74	197	875	6411
5. Neckar	1743	283	119	273	636	7193
6. Main	2139	441	151	506	1293	7365
7. Middle Rhine	1528	219	82	270	546	7422
8. Lower Rhine	3818	347	286	974	744	17270
9. Rhine Delta	38992	1243	542	1438	851	14822
SUM	58973	4206	1583	4582	6659	77714

Source: Lise and Van der Veeren (2002) downscaled from 13 to 9 regions, except for arable land, which has been derived from IGB (2003) directly.

Note: The number of Inhabitant Equivalents (IEs) is equal to the regional population times 1.5.

2.2 Pressures – emissions at source

We can derive the regional emissions from diffuse and point sources from the total numbers of animals, land and people. The easiest way to do this is by multiplying the numbers of Table 2.1 and Table 2.3 by their average emissions.[2] While this information is not actually collected from official sources, it is useful to present the numbers to verify to which extent the derived regional totals correspond with the actual emission levels. In this way, we can verify how good the calibration data fits the model. Table 2.4 and Table 2.5 present the resulting regional emissions from diffuse and point sources for the Elbe and Rhine basins.

Table 2.4 Initial diffuse and point emissions in the Elbe basin.

Region [ktonnes]	N point	N diffuse	P point	P diffuse
1. Oberelbe	4.39	57.35	0.42	11.98
2. Vlatava/Moldau	8.32	114.54	0.80	23.88
3. Ohre /Eger	2.42	36.37	0.23	7.55
4. Saale	11.02	102.48	1.06	21.16
5.Mulde-Schwarze Elster	8.70	70.92	0.84	14.64
6. Havel	13.60	62.16	1.31	12.76
7. Middle Elbe	3.34	64.48	0.32	13.30
8. Tideelbe	9.12	53.12	0.88	11.19
Total	60.92	561.40	5.87	116.46

2 The average emissions per animal, land or inhabitant equivalent can be found in Table 4.1. This table gives the characteristics of model farms and wastewater treatment plants of which the marginal costs are known.

The numbers of Table 2.3 are in the range of the numbers as calculated with MONERIS (Behrendt et al, 2000) for point sources in the period 1993–1997. However, the numbers for diffuse sources are much higher in Table 2.4. An explanation for this is the difference in definition of “initial emissions”. MONERIS call emissions, which enter the river system initial, while we call the diffuse emissions of nutrients from animals, land and people initial. This is one step backwards, as in our situation it is still possible that a large amount of emitted nutrients are retained in the soil before reaching the river network. All in all the numbers presented in Table 2.4 appear to be reasonable.

Table 2.4 also shows that the highest number of animals and land in Vlatava/Moldau translate to the highest initial diffuse emissions, while the highest point emissions are found in the most populated region Havel.

Table 2.5 Initial diffuse and point emissions in the Rhine basin.

Region [ktonnes]	N point	N diffuse	P point	P diffuse
1. Alp Rhine	8.62	38.23	0.83	8.42
2. High Rhine	9.21	64.66	0.89	13.91
3. Moselle/Sarre	10.62	84.96	1.02	17.38
4. Upper Rhine	10.58	69.73	1.02	14.41
5. Neckar	11.88	55.68	1.14	11.79
6. Main	12.16	102.45	1.17	21.41
7. Middle Rhine	12.25	46.12	1.18	9.71
8. Lower Rhine	28.51	74.43	2.75	16.49
9. Rhine Delta	24.47	146.05	2.36	32.15
Total	128.30	682.31	12.37	145.67

The numbers of Table 2.5 are in the range of the numbers as calculated with the SQR-CF (Sustainability and environmental Quality in transboundary River basins – Computational Framework) (Lise and Van der Veeren, 2002) for diffuse and point sources. The numbers for point sources in Table 2.5 are about half of the numbers as reported in Lise and Van der Veeren (2002). While this difference may be significant, we note here that (the precision of) these initial emissions do not influence the results of the model, which are presented in reduction percentages and not in absolute numbers.

As for the Elbe basin, Table 2.5 shows that the highest initial diffuse emissions are found in the Rhine Delta and the highest initial point emissions in the most populated Lower Rhine.

2.3 State/impact – transport coefficients – load to the seas

Since plants and animals living in regional surface waters take up some of the nutrients (this process is also referred to as retention), differences in the length of regional surface waters before reaching the mainstream, and the soil type in the subcatchment result in differences in retention. This means that the fraction of nutrient emissions entering the mainstream is generally lower for regions located further away from the mainstream, also a softer soil is better able to retain nutrients. One of the outcomes of the SQR project (Tanczos, 2001) is that biochemical and ecological processes hardly seem to take place in the mainstream of the Rhine, due to water flow. Because of that, retention in the mainstream is low and almost all nutrients entering this river will finally reach the river outlet.

In addition, the effects of nutrient abatement measures on surface waters differ significantly between agricultural sources and point sources. Since part of the excess amounts of nutrients applied on agricultural land is retained via biochemical processes in the soil, not all of the nutrients emitted by agricultural sources ultimately end up in the surface water. Point sources, however, are most often direct emitters. Almost all nutrients emitted by these sources end up in regional surface waters. In this study, we consider average agricultural sectors within a region, which emissions have a collective regional impact on the loads to the North Sea.

Transport coefficients are used as a linear approximation of the impact of emission from sources (animals, land, people) on the sink (North Sea) (see also Figure 1.2). This is a very simple representation of transport mechanisms used in a water quality model. They describe how much of the emissions reach the river and eventually the North Sea. In cost-effectiveness analyses such as the one presented here, simple representations are preferred, since using more sophisticated water quality models may increase both model size and calculation time considerably (see also Van der Veeren and Tol (2001) for a more extensive discussion on transport coefficients and their values). The values are presented in Table 2.6 for the Elbe and in Table 2.7 for the Rhine basin.

Table 2.6 Transport coefficients from source to coast in Elbe basin.

	N point ($T^N{}_p$)	N diffuse ($T^N{}_d$)	P point ($T^P{}_p$)	P diffuse ($T^P{}_d$)
1. Oberelbe	0.39756	0.17592	0.27645	0.00671
2. Vlatava/Moldau	0.39756	0.17592	0.27645	0.00671
3. Ohre /Eger	0.39756	0.17592	0.27645	0.00671
4. Saale	0.37974	0.17088	0.25661	0.00635
5.Mulde-Schwarze Elster	0.45833	0.20539	0.38002	0.00936
6. Havel	0.37061	0.16677	0.24668	0.00611
7. Middle Elbe	0.43144	0.19415	0.31579	0.00782
8. Tideelbe	0.41479	0.18666	0.29620	0.00733

The values in Table 2.6 are derived as follows. The load of nutrients can be calculated from the nutrient emissions by the applying following formula (See De Wit, 1999, formula 4.4):

$$\begin{cases} T_p^N = \left(1+12.58q_x^{-1.5}\right)^{-1} \\ T_d^N = T_p^N\left(0.20ur_x+0.45cr_x\right) \\ T_p^P = \left(1+45.9q_x^{-2.03}\right)^{-1} \\ T_d^P = T_p^P\left(0.009ur_x+0.025cr_x\right) \end{cases} \tag{2.1}$$

Where q_x is the area specific runoff upstream of x (see De Wit, 1999, table 4.4) and ur_x (cr_x) is the percentage of unconsolidated (consolidated) rocks upstream of x (all these values can be found in De Wit, 1999, table 4.4). The transport coefficients for the three regions in the Czech republic are the same, as De Wit (1999) does not make such a distinction.

Table 2.6 shows that there is relatively little amount of variation in the transport coefficients. An explanation for this may be that soil types in the Elbe catchment are relatively evenly distributed. We find in-between values for the transport coefficients upstream, while we find the highest values close to the main stream, namely Mulde-Schwarze Elster, Middle Elbe and Tideelbe. The lowest values are found in regions at a relatively further distance from the mainstream, namely Havel and Saale. This pattern is found for all four types of transport coefficients.

Table 2.7 Transport coefficients from source to coast in Rhine basin.

	N point (T^N_p)	N diffuse (T^N_d)	P point (T^P_p)	P diffuse (T^P_d)
1. Alp Rhine	0.86828	0.29080	0.57278	0.00669
2. High Rhine	0.93751	0.31497	0.70927	0.00887
3. Moselle/Sarre	0.82775	0.22825	0.63753	0.00545
4. Upper Rhine	0.83094	0.22270	0.62622	0.00514
5. Neckar	0.83950	0.24214	0.61611	0.00549
6. Main	0.79040	0.20554	0.58754	0.00447
7. Middle Rhine	0.82512	0.22875	0.61641	0.00555
8. Lower Rhine	0.77323	0.17547	0.53005	0.00421
9. Rhine Delta	0.21631	0.05529	0.14461	0.00876

Source: See explanation in text.

The values in Table 2.7 are derived from Lise and Van der Veeren (2002, table 5) by converting the values of 13 regions into the 9 WFD regions, using Table 2.2.

The transport coefficients for the Rhine, as presented in Table 2.7, divide the basin into three parts. The highest values are found upstream in Switzerland. Intermediate values are found midstream in Germany and France, while far out the lowest values are found in the Netherlands. This pattern is found for three types of transport coefficients, as we find the highest diffuse phosphorus emission transport coefficient for the Netherlands. The main explanation for this (extreme) difference in transport is the difference in soil type. Consolidated rocks dominate Switzerland; these are found partially in Germany and France, while the Netherlands is characterised by polders with sandy and clay soil, it is partially below the sea level, which increases the retention capacity considerably. However, the soil type has lesser bearing on the transport of phosphorus in the Rhine basin.

3. Derivation of cost abatement curves

3.1 Selection of cost effective measures

In order to find the cheapest way of obtaining a desired change in the system (response) as set out in Figure 1.2, we need an overview of costs and effects of measures, which can bring such changes about. The first step in achieving the cost effective solution is by comparing the cost effectiveness of measures. We do this by applying the following formula.[3]

$$\mathrm{CE}_i = \frac{\mathrm{Cost}_i}{\mathrm{Nred}_i} \tag{3.1}$$

Where CE_i is the cost effectiveness of measure *i* [€/kg], Cost_i is the cost of fully implementing measure *i*, while Nred_i is the total attainable reduction of nitrogen by applying the given measure. For the time being, we focus on nitrogen emission reduction, as most measures can only be targeted at nitrogen. Moreover, in the analysis, we assume that phosphorus is reduced in linear proportions with nitrogen.

In general, there exist a list of various measures for reducing nitrogen emissions from animals, land or people. We are not interested in an arbitrary overview of such measures, but need only those measures that can achieve the highest amount of reduction for the lowest amount of money: the cost-effective measures. These cost-effective measures can be found by ordering a list of measures according to their CE values, as shown in Equation (3.1). Then, the measure with the lowest CE value is selected first. After that, we only select those measures with the next lowest CE value leading to an even higher nitrogen emission reduction. This iterative process goes on until we arrive at a measure with the highest obtainable reduction percentage. This can, for example, be achieved at farms by fully closing down the farming activity. All other, less cost-effective, measures are excluded from the analysis.

3.2 Results for farm types

3.2.1 Farm types

Information on costs and effects of measures at farms is available via a very detailed study of Dutch farms by Leneman et al (1992). From this study can be extracted lists of costs and effects of measures to reduce nutrient (N and P) emissions at farms in the Netherlands. As these costs and effects are quite different for various farming activities, the authors divided the Dutch farming sector into 8 different farm types. For instance, the story is quite different for farms at clay or sandy soils and the kind of animal also matters. Moreover, the following farm types are distinguished.

[3] It is also possible to calculate the cost effectiveness by dividing the effect by the cost [kg/€]. This does not have any influence on the result.

1. Broiler farms.
2. Hen farms.
3. Arable farms on clay soil.
4. Arable farms on sandy soil.
5. Dairy farms on clay soil.
6. Dairy farms on sandy soil.
7. Pig breeding farms.
8. Pig feeding farms.

These farm types are used to verify to which extent, on the average, nutrient emissions can be reduced at the farm level and at which cost. A study with such a level of detail on costs of measures at farms is the best we know, and, due to the lack of alternative data, we assume that these numbers are representative for the whole Rhine and Elbe basin.

3.2.2 Data on costs and effects

The available data for the eight farm types, mentioned above, consists of a list of possible measures per farm type. For each measure, the total costs and the resulting emission reduction of ammonia, nitrate and phosphorus is estimated. The list of measures consists of exclusive packages, which means that when one measure package is fully implemented, no other measure package can be implemented. The list of measures also includes the option to fully close the farm –quota restrictions– representing the most rigorous and highest obtainable nutrient emission reduction at the farm level.

Table 3.1 presents the costs, initial emissions, effects (obtainable reduction percentage) and the cost effectiveness (CE) for cost-effective measures, as derived by applying the method of Section 3.1. The cost effective measures are presented per farm type and ordered according to their CE-value. Table 3.1 shows that we find for each of the 8 farm types at least three cost-effective measures, while we find 8 cost-effective measures for dairy farms on clay. At pig feeding and breeding farms it is also possible to reduce phosphorus simultaneously with nitrogen.

The description of the measures in Table 3.1 refers to measure number(s), of which the meaning is presented in Table 3.2.

As Table 3.1 shows, the list of measures at farm types also includes some measures where nutrient emissions can be reduced at negative cost. This implies that Leneman et al (1992) find options where farmers can earn money and reduce emissions at the same time. This is, generally, far from sufficient for achieving the required emission reduction, as set out in the OSPAR agreement.

Table 3.1 Costs and effects of cost effective measures per farm type.

		Description	Costs [€]	N0 [kg]	P0 [kg]	red % N	red % P	cost effectiveness [€/kg N]
1	Broilers	Measure 1	-1224			12.1		-8.16
		Measures 1 + 2	33241			91.3		29.50
		Farm closure	45000	1235	0			36.44
2	Hens	Measure 1	0			12.6		0.00
		Measures 1 + 3	2155			50.1		5.97
		Measure 2	31018			90.0		47.79
		Measures 1 + 2	39186			91.3		59.55
		Farm closure	45000	721	0			62.41
3	Arable clay	Measure 1	-248			37.0		-0.43
		Measure 2	1184			73.1		1.05
		Measures 2 + 4	1898			78.8		1.56
		Measures 2 + 3	3530			89.5		2.55
		Measures 2 + 3 + 4	4246			95.1		2.88
		Farm closure	80000	1548	573			51.68
4	Arable sand	Measure 1	-375			17.7		-0.47
		Measures 1 + 4	430			22.1		0.43
		Measures 1 + 3	1219			49.5		0.54
		Measures 1 + 3 + 4	2025			54.6		0.82
		Measures 2 + 3	2996			79.5		0.83
		Measures 2 + 3 + 4	3801			84.6		0.99
		Farm closure	80000	4547	506			17.59
5	Dairy clay	Measure 6	2278			40.6		1.63
		Measure 5	3373			45.1		2.17
		Measures 2 + 5	5465			49.6		3.20
		Measures 3 + 5	9548			56.6		4.90
		Measures 4 + 5	13062			57.5		6.60
		Measures 4 + 5 + 7	15627			66.6		6.82
		Measures 3 + 4 + 5	19142			67.3		8.27
		Farm closure	60000	3439	702			17.45
6	Dairy sand	Measure 2	1364			17.6		1.78
		Measure 6	2274			26.9		1.95
		Measures 2 + 5	5381			47.7		2.60
		Measures 3 + 5	8947			58.4		3.53
		Measures 3 + 4 + 5	20217			68.7		6.78
		Farm closure	60000	4342	915			13.82
7	Pig breeding	Measure 1	132			8.3	2.5	0.67
		Measure 2	434			17.2	2.5	1.06
		Measures 2 + 3	1350			21.0	2.5	2.71
		Measures 4 + 5	7043			56.7	86.2	5.22
		Farm closure	45000	2381	932			18.90
8	Pig feeding	Measure 2	-2856			17.2		-3.53
		Measures 2 + 3	-1149			19.6		-1.25
		Measures 2 + 4	3095			29.8		2.20
		Measures 4 + 5	9254			66.8	86.2	2.94
		Farm closure	45000	4709	1191			9.56

Note: N0 and P0 are initial emissions of nitrogen and phosphorus. The meaning of the measure numbers is given in Table 3.2.

Table 3.2 List of cost effective measures per farm type.

Farm type	Measure number	Description
Poultry	1	3-stage feeding with protein restriction
	2	Air-washers (90% reduction)
	3	Conveying belt above batteries
Arable land	1	Spring application
	2	No manure application 0% potato yield reduction
	3	Reduction of nitrogen fertilisation on potatoes by 50%
	4	Green manure
Dairy cows	1	Feeding according to protein needs
	2	Changing diet to 300 kg N application on pasture and measure 1
	3	Changing diet to 200 kg N application on pasture and measure 1
	4	Manure flushing system high reduction
	5	Shorter application period and manure injection
	6	Shorter application period and rain off
	7	Having the cattle during the whole year in the stable
Pigs	1	Multiple-stage feeding
	2	Multiple-stage feeding with protein restriction
	3	Small stable adjustments (50% reduction)
	4	Spring application and direct under ploughing
	5	Manure disposal

3.3 Results for wastewater treatment plants

It is also possible to derive the cost effective measures for wastewater treatment plants in the Netherlands (Van der Veeren, 2002). At wastewater treatment plants, P and N can be reduced with separate measures. For the case of reducing P, the CE in Equation (3.1) is adjusted by substituting Pred for Nred. Table 3.3 shows for wastewater treatment plants the costs, reduction percentages, CE per measure and the total initial emissions for N and P.

The cost and effects of the cost-effective measures in Table 3.3 are based on the assumption that wastewater treatment plants already reduce 67% P and 52% N and only give the cost for installing an *additional* capacity for a further removal of nutrients. Table 3.3 shows that it is possible to reduce the current effluent of phosphorus by 86.7%, while the current effluent of nitrogen can still be reduced by 54.5%.

The meaning of the measure numbers as mentioned in the description of Table 3.3 is presented in Table 3.4.

Table 3.3 Costs and effects of cost effective measures on wastewater treatment plants.

	Description	Costs [1000 €]	red %	cost effectiveness [€/kg]
Phosphorus:	Measure 5	41124	34.6	32.99
	Measures 5 + 3	56305	44.9	34.76
Total P	Measures 5 + 3 + 1	77614	57.2	37.68
emissions:	Measures 6 + 3 + 1	173570	74.5	64.69
3605	Measures 6 + 4 + 1	211728	79.6	73.78
tonnes	Measures 6 + 4 + 2	267907	85.7	86.70
Nitrogen	Measures 1 + 5 + 10	2079	2.3	2.46
	Measures 1 + 5 + 10 + 11	55164	19.9	7.40
Total N	Measures 1 + 5 + 10 + 11 + 6	66048	22.9	7.72
emissions:	Measures 1 + 5 + 10 + 12 + 6	114567	35.5	8.63
37400	Measures 1 + 5 + 10 + 12 + 7 + 13	152148	44.6	9.12
tonnes	Measures 1 + 5 + 10 + 12 + 7 + 14 + 2 + 8	189397	52.0	9.73
	Measures 1 + 5 + 10 + 12 + 7 + 14 + 3 + 9 + 4	205015	54.5	10.05

Table 3.4 List of cost effective measures for wastewater treatment plants.

WWTP-N	Description:
1	78% N removal at small size oxidation ditches
2	67% N removal at small size activated sludge
3	78% N removal at small size activated sludge
4	78% N removal at small size oxidation beds
5	78% N removal at medium size oxidation ditches
6	67% N removal at medium size activated sludge
7	78% N removal at medium size activated sludge
8	67% N removal at medium size oxidation beds
9	78% N removal at medium size oxidation beds
10	78% N removal at large size oxidation ditches
11	67% N removal at large size activated sludge
12	78% N removal at large size activated sludge
13	67% N removal at large size oxidation beds
14	78% N removal at large size oxidation beds
WWTP-P	
1	Precipitation at small size plants
2	Precipitation and filtration at small size plants
3	Precipitation at medium size plants
4	Precipitation and filtration at medium size plants
5	Precipitation at large size plants
6	Precipitation and filtration at large size plants

3.4 Results for wetlands

As a final option it is also possible to increase the retention of nutrients in the catchments by constructing new wetlands. In the SQR project (Tanczos, 2001) about 10% of the arable land (40000 km^2) in the Rhine catchment has been found suitable for that purpose. The annual cost of creating new wetlands, including investment and maintenance, in the Rhine river basin is estimated at 2300€/ha/year. This amount of money is required for the case where the maximum percentage (10%) of total arable land is devoted to wetlands. This estimate assumes that wetlands are mowed regularly and the waste material is transported in such a way that it will not contribute to the load to the North Sea. It is also assumed that wetlands can only be created in streams with a maximum discharge of 20 m^3/sec in relatively flat areas (Ibid.). Table 3.5 shows the total cost of devoting different fractions of arable land to wetlands in the Rhine river basin.

Table 3.5 Costs and effects of wetland creation in the Rhine river basin.

Percentage of arable land devoted to wetlands	Reduction in N load	Reduction in P load	Costs [million €/year]	Cost-effectiveness [€/% N reduction]
1.1%	10.2%	6.6%	100.69	987
2.0%	17.1%	11.2%	183.07	1071
4.4%	30.6%	21.2%	402.76	1316
10.0%	47.8%	35.8%	915.36	1915

Table 3.5 shows that when 10% of arable land in the Rhine basin is devoted to wetland construction, as reduction of 48% N load and 36% P load is possible. The cost is 915 million euros. The amount of reduction is given in percentages here, as the absolute amount of reduction that can be achieved depends on the concentration of nutrients that flows through the wetlands. The reduction of P is somewhat lower than N, as P is mainly transported via sediments, while nitrogen is generally transported in a solved form.

If we compare the cost effectiveness in Table 3.5 with the cost effectiveness in Table 3.1 and Table 3.3, we can see that the cost of load reduction to the North Sea by constructing wetlands is an economically viable alternative for emission reductions at the source by wastewater treatment plants and farms, of which only a fraction contributes to the load in the North Sea.

3.5 Cost abatement curves

The cost abatement curves for each farm type are shown in Figure 3.2, for wastewater treatment plants are shown in Figure 3.3 and for wetlands in Figure 3.4. Figure 3.1 illustrates how cost abatement curves are constructed from measures and how these curves are approximated by a quadratic curve.

Figure 3.1 is built up from three curves. First, the gray curve is an angled step function, which shows 5 distinct measures. Second, this curve can be turned into a (continuous) cost abatement curve, when we allow for fraction of two consecutive measures to be taken, where these two fractions add up to one (the solid black line). Third, a quadratic curve can be fitted through this solid black line. This leads to the smooth dotted line.

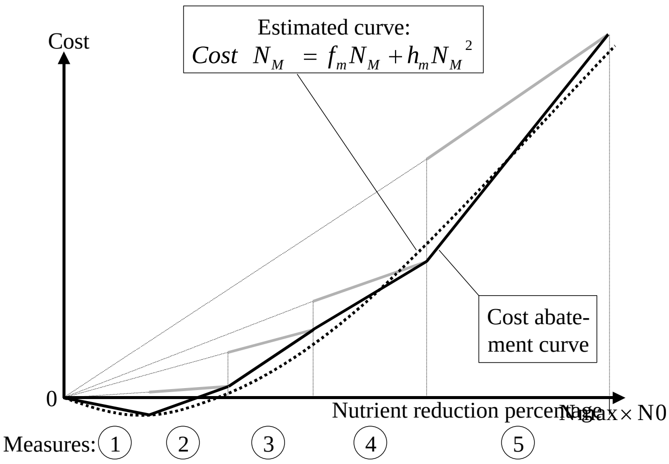


Figure 3.1 Link between cost abatement and estimated curve.

The shape of the cost abatement curves is a typical u-curve, where the cost of reduction accelerates in the amount of reduction. The cost abatement curves in Figure 3.2 initially decrease for four farm types: broiler farms, arable farms (both on sand and clay) and pig breeding farms. This is the case where options exist at the farm level to take measures and also earn money (see also Table 3.1). Figure 3.2 also shows the estimated curves as used in the model (see Chapter 4). This shows that costs are sometimes over- and sometimes underestimated.

Figure 3.3 shows the cost abatement curves for nitrogen and phosphorus reduction at wastewater treatment plants. The estimated curve fits very well through the data for nitrogen. The cost abatement curve for phosphorus bends around two ktonnes P reduction. At this point, in order to achieve more reduction, substantial investments have to be undertaken, abruptly increasing the marginal costs. Simulations with the model show that relatively lower P reductions are required in the Rhine basin (represented by the curve which goes smoothly through the first two-third), and relatively higher P reductions in the Elbe basin (represented by the curve which goes smoothly through the last third).

Figure 3.4 has three lines, which can be best interpreted by following the gridlines. On the y-axes is depicted the amount of money required for devoting a percentage of total arable land in the basin (varying between 0% to 10%). At the same cost, one can also read the percent reduction in P (varying between 0% and 36%) and the percent reduction in N (varying between 0% and 48%).

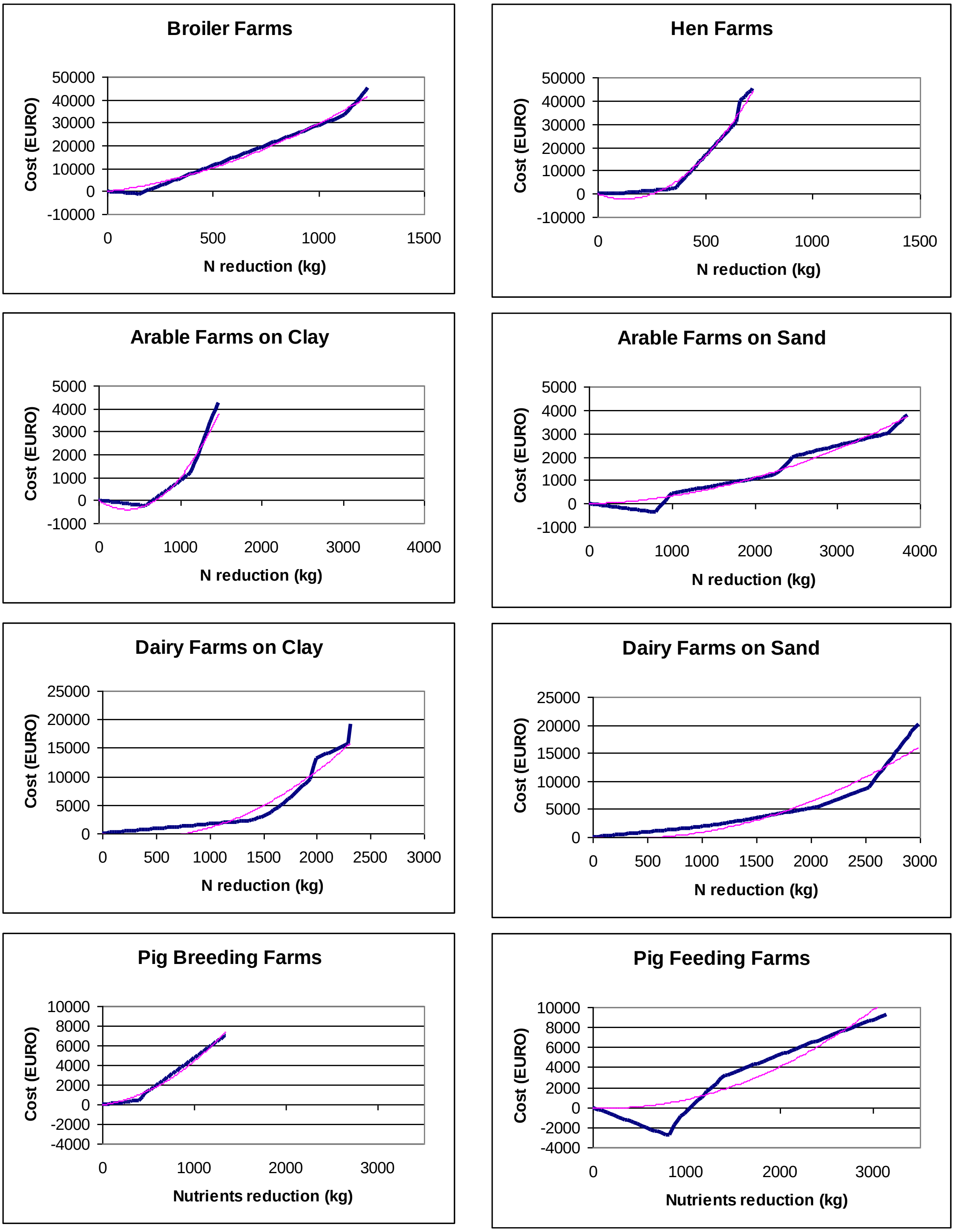


Figure 3.2 Cost abatement curves per farm type.

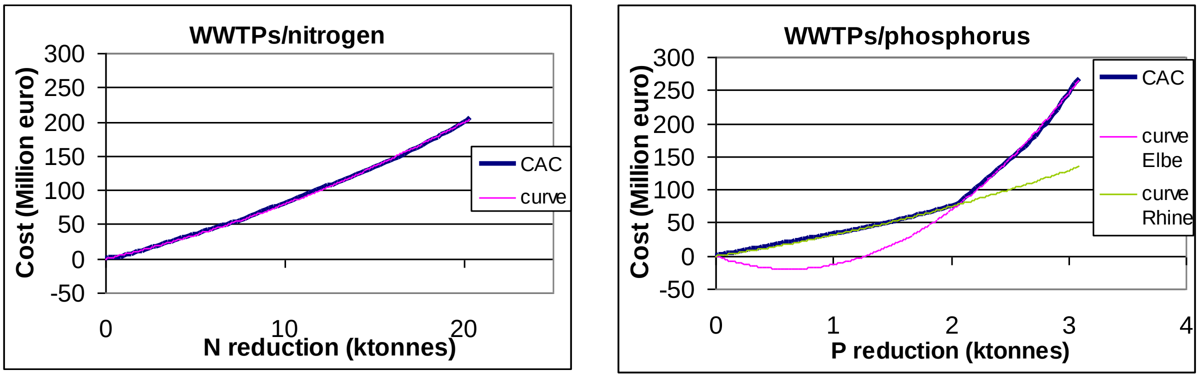


Figure 3.3 Cost abatement curves for wastewater treatment plants.

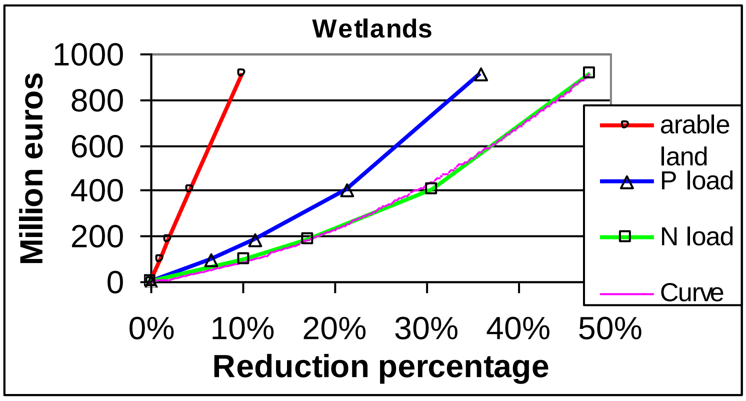


Figure 3.4 Cost abatement curves for wetlands.

4. Response – derivation of marginal costs

The cost abatement curves of Chapter 3 are now needed to estimate the marginal costs of nutrient emission reduction at various sources.

The cost abatement curves, as presented in Figure 3.2 and Figure 3.3, are at the level of an average farm or wastewater treatment plant. The main characteristics of these average farms and wastewater treatment plants are summarised in Table 4.1, namely their initial N and P emissions, the number of animals or hectares of land per farm and the number of connected inhabitant equivalents for wastewater treatment plants. For convenience, Table 4.1 also presents the maximum reduction fraction (Nmax, Pmax) per farm or wastewater treatment plant by taking (technological) measures.

Table 4.1 Initial nitrogen and phosphorus emissions, average farm size, maximal achievable emission reduction percentage with measures, and farm value at 8 farm types and wastewater treatment plants.

Farm type	N0 [kg]	P0 [kg]	ASA	Nmax [%]	Pmax [%]	Farm value [€]
Broiler farms	1235	0	24236	91.3	0	45000
Hen farms	721	0	27000	91.3	0	45000
Arable farms on clay	1548	573	43.6	95.1	0	80000
Arable farms on sand	4547	506	65.5	84.6	0	80000
Dairy farms on clay	3439	702	64.2	67.3	0	60000
Dairy farms on sand	4342	915	61.2	68.7	0	60000
Pig breeding farms	2381	932	120	56.7	86.2	45000
Pig fattening farms	4709	1191	576	66.8	86.2	45000
WWTPs phosphorus		3605000	22654000		85.7	-
WWTPs nitrogen	37400000			54.5		-

Source: ASA (Average Size of emitting Activity) from Van der Veeren (2002, table 3.10), the other numbers are taken from Table 3.1 and Table 3.3.

As mentioned before, cost abatement curves are typical u-curves, where the cost of reduction accelerates in the amount of reduction. A parabola or quadratic function can reasonably approximate such a u-curve. A parabola is preferred over a linear function, otherwise the cost-effective solution becomes a trivial corner solution, where reduction measures are either fully taken or not at all. Here we are interested in the trade-off among sectors and regions. A more complex function than the parabola is also not considered here, as it cannot be solved in the MATLAB programming language, which we have chosen for solving the model.

Now we can derive the so-called marginal costs, by trying to find the best fitting parabola through the cost abatement curves in Figure 3.2. This is equal to fitting the following quadratic functions:

$$Cost\ \ N_M \ = f_m N_M + h_m {N_M}^2 \tag{4.1}$$

Here, we have data on the variables Cost(N_M) and N_M, while parameters f_m and h_m have to be chosen in such a way that the parabola is as close as possible to the cost abatement curves. Figure 3.2 shows the result. The same reasoning holds for the other two equations in (4.1).

We have included linear terms in (4.1) as the optimum of the cost abatement curves need not go through the origin, but the (cost abatement) curve does. The CENER model, which is sufficiently flexible to deal with cost abatement functions with a linear term, includes Equation (4.2).

The total value per farm type and their total initial emissions are used (rows which start with “farm closure” in Table 3.1) to derive the marginal costs for quota restriction at farms. This relation is approximated analytically by calculating a quadratic function through three points, namely the origin (0,0), the point with full farm closure (a,b) and the point with 50% farm closure (c,d). In the third point we assume the costs to be 10% lower, to capture the idea that a gradual closure of the farm is not totally linear. The following equation is solved:

$$Cost\ \ N_Q\ = f_q N + h_q N_Q^{\ 2}$$
$$\text{where } f_q = \tfrac{da^2 - bc^2}{ca^2 - c^2 a};\, h_q = \tfrac{bc - da}{ca^2 - c^2 a} \qquad (4.2)$$

The goodness of fit of Equation (4.2) is depicted in Figure 4.1, which shows that the quadratic approximation of a linear relationship leads to a marginal underestimation of the costs.

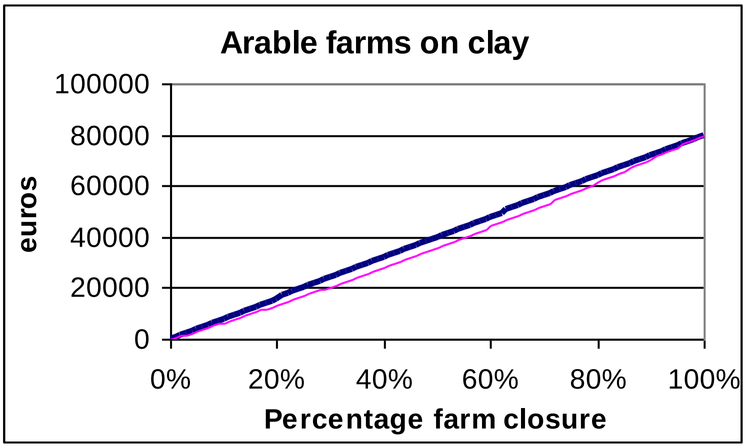


Figure 4.1 A representative cost abatement curve and its estimation for farm closures.

The cost abatement curves for nitrogen and phosphorus reduction through measures at wastewater treatment plants are also derived analytically, as done for farm closures. These curves always go through the origin and the point with full reduction. The third point is (35.5%, 114.6) for nitrogen, (34.6%, 41.1) for phosphorus reduction in the Rhine basin and (57.2%, 77.6) for phosphorus reduction in the Elbe basin.

$$\begin{aligned} Cost \quad N &= f_n N + h_n N^2; \\ Cost \quad P &= f_p P + h_p P^2 \end{aligned} \qquad (4.3)$$

Measures at the farm level and the construction of wetlands are assumed to lead to a joint reduction of N and P in fixed proportions. Hence, it is assumed that these emission reductions are linked linearly:

$$\begin{aligned} P_M &= g_m N_M; \text{ where } & g_m &= \tfrac{\text{Pmax}}{\text{Nmax}} \tfrac{\text{P0}}{\text{N0}} \\ P_Q &= g_q N_Q & g_q &= \tfrac{\text{P0}}{\text{N0}} \\ p &= g_w n & g_w &= \tfrac{\text{Pmaxw}}{\text{Nmaxw}} \end{aligned} \qquad (4.4)$$

Table 4.2 shows the estimated parameters of Equation (4.1), and the calculated parameters of Equations (4.2) and (4.4) for all farm types and wastewater treatment plants, fitting the cost abatement curves of Figure 3.2 and Figure 3.3.

Table 4.2 Marginal costs for measures and quota restrictions at farms and wastewater treatment plants, and the link between nitrogen and phosphorus emissions.

Farm type	f_m	SE	h_m	SE	f_q	h_q	g_m	g_q
Broiler farms	11.772	(0.811)	0.0178	(0.0008)			0	0
Hen farms	-32.806	(1.659)	0.131	(0.003)			0	0
Arable farms on clay	-2.267	(0.101)	0.00330	(0.00009)	41.344	0.006677	0.3702	0
Arable farms on sand	0.109	(0.039)	0.000224	(0.000013)	14.075	0.000774	0.1113	0
Dairy farms on clay	-3.411	(0.382)	0.00446	(0.00021)	13.958	0.001015	0.2041	0
Dairy farms on sand	-1.301	(0.300)	0.00224	(0.00013)	11.055	0.000637	0.2107	0
Pig breeding farms	1.328	(0.140)	0.00315	(0.00013)	15.120	0.001588	0.3914	0.5951
Pig fattening farms	-0.422	(0.291)	0.00123	(0.00012)	7.645	0.000406	0.2529	0.3264
Wastewater treatment plants:			f_n	h_n	f_p	h_p		
WWTPs nitrogen			5.9587	2.01E-07				
WWTPs phosphorus	(Rhine)				-60.859	4.78E-05		
WWTPs phosphorus	(Elbe)				25.821	5.73E-06		

Source: Based on regressions in SPSS with data from Leneman et al (1992).

The parameter values of Equations (4.2) and (4.3) as presented in Table 4.2 are estimates at the farm and wastewater treatment plant level. In order to obtain the values at the regional level in the catchment, the estimated parameters have to be scaled as follows, where a curl (~) on the parameter denotes the resulting parameter after scaling:

$$\tilde{h}_{s,r} = h \times \frac{\text{ASA}_s}{\text{SAR}_{s,r}}; \; \tilde{f}_{s,r} = f \qquad (4.4)$$

where ASA_s stands for Average Size of emitting Activity for sector *s* (see Table 4.1), while $\text{SAR}_{s,r}$ represents the Size of Activity of sector *s* in Region *r*. These values are respectively given in Table 1.1 and Table 1.3 for the Elbe and Rhine catchment.

We can also derive the marginal costs for wetlands, by trying to find the best fitting parabola through the cost abatement curves in Figure 3.4. This is equal to fitting the following quadratic functions:

$$Cost(n) = f_w n + h_w n^2 \tag{4.5}$$

Table 4.3 shows the estimated parameter values of Equations (4.5) for wetlands.

Table 4.3 Maximal achievable retention and marginal cost(h_w) for wetlands.

	Nmax	Pmax	f_w [M€/reduction %]	h_w [M€/reduction %^{2}]
Wetlands	47.8	35.8	0.06003	0.2750

Source: Based on regressions in SPSS with data from Tanczos (2001).

5. Implementation of the CENER model in MATLAB

The information presented in Chapters 2–4 is entered into the CENER model. This Chapter completes the description of the CENER model. The CENER model distinguishes among nitrogen and phosphorus emission reduction, by measures at point sources, wetlands, diffuse sources, and quota restrictions at diffuse sources (i.e. partial farm closure). The purpose of the CENER model is to reduce emissions at sources where it is cheapest to do so, in order to achieve a desired load to the coastal seas at least cost. Figure 5.1 shows the link between the DPSIR representation of the catchment in Figure 1.2 to the main variables and parameters of the CENER model.

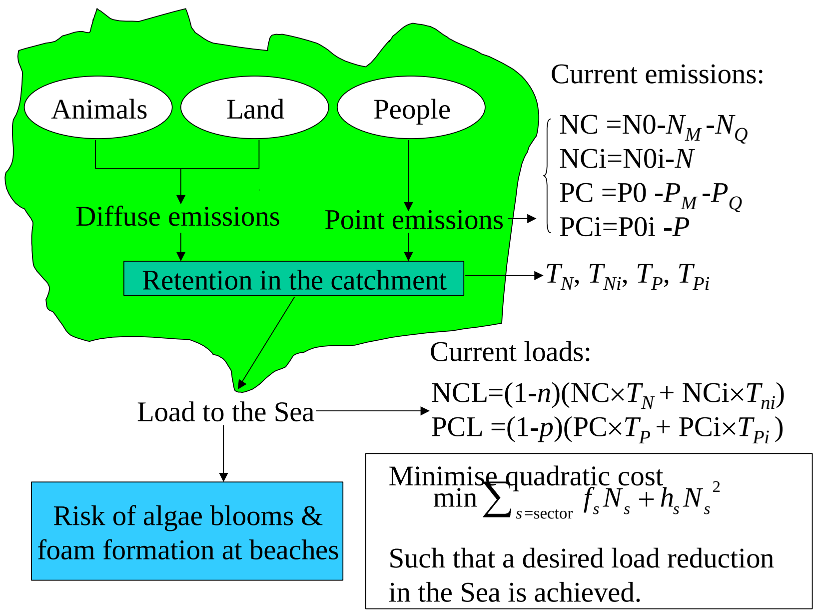


Figure 5.1 CENER model; the catchment consists of one region.

To unfold the precise structure of the CENER model, we first present the model structure for three intrinsically different sectors, namely farms, wastewater treatment plants and wetlands. These three sectors need to be treated quite differently as we explain below. But once these differences have been pointed out, it becomes straightforward to extend the model to multiple regions and multiple sectors, which is nothing more than ‘expanding a matrix’, as is explained in the following subsection.

Table 5.1 shows eight different variables in the CENER model, which represent additional nutrient reductions at the source level, with respect to 1985 emissions levels.

Table 5.1 Variables in the optimisation model.

nitrogen	phosphorus	Description
N_M	P_M	emission reduction by measures at farms [kton]
N_Q	P_Q	emission reduction by quota restrictions on farms [kton]
N	P	emission reduction by measures at waste water treatment plants [kton]
n	p	load reduction in sea due to nutrient wetland retention [fraction]

The variables in Table 5.1 are conditioned by the parameters in Table 5.2.

Table 5.2 Parameters in the optimisation model.

nitrogen	phosphorus	Description
T_N	T_P	Transport coefficient at farms [fraction]
T_{Ni}	T_{Pi}	Transport coefficient at waste water treatment plants [fraction]
h_m	h_q	Quadratic term in cost function for measures at farms [M€/kton^2]
h_n	h_p	Quadratic term in cost function for waste water treatment plants [M€/kton^2]
h_w		Quadratic cost for reducing a fraction of the load through wetlands [M€]
g_m		The amount of N required to reduce a unit of P for measures at farms [fraction]
g_q		The amount of N required to reduce a unit of P by quota restrictions on farms [fraction]
g_w		The amount of N required to reduce a unit of P for wetlands [fraction]
Ntar	Ptar	Reduction target for nutrient load to the North Sea [fraction]
Napp	Papp	Approximation of nutrient reduction through wetlands [fraction]
$Napp^-$	$Papp^-$	Lower border of approximation of nutrient reduction through wetlands [fraction]
$Napp^+$	$Papp^+$	Upper border of approximation of nutrient reduction through wetlands [fraction]
Nmax	Pmax	Maximum fraction of reducible emissions by measures at farms [fraction]
Nmaxi	Pmaxi	Maximum fraction of reducible emissions by waste water treatment plants [fraction]
Nmaxw	Pmaxw	Maximum fraction of reducible load to the North Sea by wetlands [fraction]
N0	P0	Initial emissions by farms [kton]
N0i	P0i	Initial emissions by waste water treatment plants [kton]
AeqN	AeqP	Initial load to the North Sea [kton]
NC	PC	Current diffuse emissions [kton]
NCi	PCi	Current point emissions [kton]
NCL	PCL	Current load to the sea [kton]

The CENER model trades off among joint N and P reductions, measures and quota restrictions at the farm level, measures at wastewater treatment plants and wetland construction. As explained in Section 4, measures at the farm level and the construction of wetlands are assumed to lead to a joint reduction of N and P in fixed proportions, using Equation (4.5). These linear links reduce the number of variables in the model from 8 to

5, as three variables in the model can always be substituted away by other variables by applying Equation (4.5).

From now on, we continue to work with N_M, N_Q, N, P and n. The costs to be minimised are equal to the cost of reducing nutrients at farms through measures or quota restrictions, measures at wastewater treatment plants or by constructing wetlands. This relation is established by combining Equations (4.2), (4.3) and (4.7) into Equation (5.1).

$$Cost\ \ N_M, N_Q, N, P, n\ = Cost\ \ N_M\ \ + Cost\ \ N_Q\ \ + Cost\ \ N\ \ + Cost\ \ P\ \ + Cost\ \ n \tag{5.1}$$

In practice, some agricultural activities may be able to apply measures that would reduce costs and nutrient emissions at the same time. This means that farmers do not produce efficiently in the initial situation (they can earn more money and emit lesser nutrients at the same time). The CENER model allows for this via Equation (4.2).

The assumption of a quadratic cost abatement function implies that a measure costs relatively more if the level of implementation increases. The quadratic form also avoids an undesired and anti-intuitive solution where measures or quota restriction are either implemented for 100% or 0%, a so-called corner solution.

Besides the cost minimising objective, restrictions are added to the CENER model. In order to integrate measures and quota restrictions, we include the following inequality constraint:

$$N_M \leq \mathrm{Nmax}\ \ \mathrm{N0} - N_Q \tag{5.2}$$

Equation (5.2) guarantees that measures are only applied on the farms, which remain after quota restrictions. This means that nutrient emission reductions through measures at farms should not exceed the maximum obtainable emission reduction of the current emissions, which are the initial emissions minus imposed quota restrictions.

The initial load to the sea (AeqN and AeqP) is determined by multiplying transport coefficients with initial emission levels. Equation (4.4) shows this.

$$\begin{aligned} \mathrm{AeqN} &= T_N \mathrm{N0} + T_{Ni}\mathrm{N0i} \\ \mathrm{AeqP} &= T_P \mathrm{P0} + T_{Pi}\mathrm{P0i} \end{aligned} \tag{5.3}$$

To study the effect of emission reduction on the load to the North Sea, the N emission reductions due to measures at farms (N_M) and quota restrictions (N_Q) are multiplied by the transport coefficient for N emissions from agricultural sources (T_N). Additionally, the impact of N abatement by wastewater treatment plants (N) is multiplied by the transport coefficients for the wastewater treatment plants (T_{Ni}). Hence the reduction in the initial load, due to measures at farms and wastewater treatment plants, is equal to: (T_N (N_M+N_Q)+$T_{Ni}N$). Constructing wetlands can further reduce this resulting current load. As n is the fraction of nitrogen reduction through wetlands, an additional amount of n(AeqN–T_N (N_M+N_Q)–$T_{Ni}N$) units of nitrogen can be reduced via new wetlands. Finally the total reduction in the load needs to be at least as large as the required reduction target. This is expressed in the following inequality.

$$T_N N_M + T_N N_Q + T_{Ni} N + n \;\; \mathrm{AeqN} - T_N N_M - T_N N_Q - T_{Ni} N \;\; \geq \mathrm{Ntar} \times \mathrm{AeqN} \tag{5.4}$$

However, inequality (5.4) is non-linear (we have a multiplication between *n* and (N_M, N_Q, N)) and cannot be solved directly by quadratic programming (but as we show below, it can be solved by iteration). In order to get around this problem, it is possible to use the first order Taylor approximation of f(n)=(Ntar–n)/(1–n) around Napp, which lies between zero and Ntar. By substituting (Ntar–Napp)/(1–Napp) – (1–Ntar)(n–Napp)/(Napp–1)^2 for f(n) and by substituting Equation (4.4), we can derive the following two *linear* inequalities, where we apply the same reasoning as above on P.

$$\begin{aligned} T_N N_M + T_N N_Q + T_{Ni} N + \mathrm{AeqN} \times n \times \tfrac{1-\mathrm{Ntar}}{1-\mathrm{Napp}\;^2} \quad & \geq \quad \tfrac{\mathrm{Ntar}-2\,\mathrm{NtarNapp}+\mathrm{Napp}^2}{1-\mathrm{Napp}\;^2} \times \mathrm{AeqN} \\ T_P g_m N_M + T_P g_q N_Q + T_{Pi} P + \mathrm{AeqP} \times g_w n \times \tfrac{1-\mathrm{Ptar}}{1-\mathrm{Papp}\;^2} \quad & \geq \quad \tfrac{\mathrm{Ptar}-2\,\mathrm{PtarPapp}+\mathrm{Papp}^2}{1-\mathrm{Papp}\;^2} \times \mathrm{AeqP} \end{aligned} \tag{5.5}$$

Equation (5.5) guarantees that the reduction target for N and P (Ntar and Ptar) are *at least* met. It is possible that in a cost-optimal solution either more N or more P is reduced. This may be cheaper as N and P are reduced through wetlands and farms in fixed proportions. In the case of a strict equality in (5.5) the model may not find a solution.

It is also possible to calculate an optimal solution without wetlands. Due to the linear Taylor approximation around the reduction target, the model needs to be changed. In that case Equation (5.5) has to be replaced by the following –simpler– expression:

$$\begin{aligned} T_N N_M + T_N N_Q + T_{Ni} N \quad & \geq \quad \mathrm{Ntar} \times \mathrm{AeqN} \\ T_P g_m N_M + T_P g_q N_Q + T_{Pi} P \quad & \geq \quad \mathrm{Ptar} \times \mathrm{AeqP} \end{aligned} \tag{5.6}$$

Finally, it is necessary to (naturally) restrict some of the variables in the model, in order to complete the CENER model:

$$\begin{aligned} & N_M \geq 0; N_Q \geq 0; N \geq 0; P \geq 0; n \geq 0; \\ & N_Q \leq \mathrm{N0};\; N \leq \mathrm{Nmaxi} \times \mathrm{N0i};\; P \leq \mathrm{Pmaxi} \times \mathrm{P0i};\; n \leq \mathrm{Nmaxw} \end{aligned} \tag{5.7}$$

These restrictions require nutrient abatement to be non-negative, and less than 100% of the technical constraints. There is no explicit upper boundary for N_M as this is already guaranteed by Equation (5.2).

The (quadratic programming) CENER model can also be written in matrix form, as follows:

$$
\begin{aligned}
&\min_X \; fX + X^T HX \\
&\text{such that} \\
&AX \leq b; \\
&LB \leq X \leq UB
\end{aligned}
\tag{5.8}
$$

Here X is the vector of nutrient emission reductions. X^T means the transpose of X. LB and UB are respectively the lower and upper bound of variable X. H is a matrix with quadratic parameters; f is the vector with linear parameters. A is a matrix with inequality constraints, where vector b contains the upper bounds.

The matrices in Equation (5.8) have the following shape, which can be derived by combining Equations (5.1), (5.2), (5.5) and (5.7):

$$
\begin{gathered}
X = \begin{bmatrix} N_M \\ N_Q \\ N \\ P \\ n \end{bmatrix}; f = \begin{bmatrix} f_m \\ f_q \\ f_n \\ f_p \\ f_w \end{bmatrix}; H = \begin{bmatrix} h_m & 0 & 0 & 0 & 0 \\ 0 & h_q & 0 & 0 & 0 \\ 0 & 0 & h_n & 0 & 0 \\ 0 & 0 & 0 & h_p & 0 \\ 0 & 0 & 0 & 0 & h_w \end{bmatrix}; b = \begin{bmatrix} -\mathrm{AeqN} \times \frac{\mathrm{Ntar} - 2\mathrm{NtarNapp} + \mathrm{Napp}^2}{(1 - \mathrm{Napp})^2} \\ -\mathrm{Ptar} \times \frac{\mathrm{Ptar} - 2\mathrm{PtarPapp} + \mathrm{Papp}^2}{(1 - \mathrm{Papp})^2} \\ \mathrm{N0} \times \mathrm{Nmax} \end{bmatrix}; \\
A = \begin{bmatrix} -T_N & -T_N & -T_{Ni} & 0 & -\mathrm{AeqN} \times \frac{1 - \mathrm{Ntar}}{(1 - \mathrm{Napp})^2} \\ -g_m \times T_P & -g_q \times T_P & 0 & -T_{Pi} & -\mathrm{AeqP} \times g_w \times \frac{1 - \mathrm{Ptar}}{(1 - \mathrm{Papp})^3} \\ 1 & \mathrm{Nmax} & 0 & 0 & 0 \end{bmatrix}; \\
LB = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \end{bmatrix}; UB = \begin{bmatrix} \infty & \mathrm{N0} & \mathrm{N0i} \times \mathrm{Nmaxi} & \mathrm{P0i} \times \mathrm{Pmaxi} & \mathrm{Nmaxw} \end{bmatrix}
\end{gathered}
\tag{5.9}
$$

We do not know a priori the right value of Napp (the linearisation of nitrogen reduction though wetland construction n, as mentioned in Equation (5.5)). However, this value can be found by iterating the full model and by comparing the total costs. Therefore, we take Napp^+ = Ntar as the upper border and Napp^- = 0 as the lower border for Napp and calculate the costs of the upper border C^+ and the costs of the lower border C^-. In each iteration step these costs are compared with each other and the borders are adjusted accordingly, with Napp = $(\mathrm{Napp}^+ - \mathrm{Napp}^-)/2$:

$$
\begin{aligned}
&\text{if } C^- > C^+ \text{then} \quad && \begin{cases} \mathrm{Napp}^- = \mathrm{Napp} \\ \mathrm{Napp}^+ = \mathrm{Napp} + \frac{\mathrm{Napp}^+ - \mathrm{Napp}^-}{2} \end{cases} \\
&\text{otherwise} && \begin{cases} \mathrm{Napp}^- = \mathrm{Napp} - \frac{\mathrm{Napp}^+ - \mathrm{Napp}^-}{2} \\ \mathrm{Napp}^+ = \mathrm{Napp} \end{cases}
\end{aligned}
\tag{5.10}
$$

After about 15 steps the difference between Napp^+ and Napp^- is small enough for obtaining the desired value for Napp.

In the case without wetlands, the matrices in Equation (5.9) simplify to:

$$X = \begin{bmatrix} N_M \\ N_Q \\ N \\ P \end{bmatrix}; f = \begin{bmatrix} f_m \\ f_q \\ f_n \\ f_p \end{bmatrix}; H = \begin{bmatrix} h_m & 0 & 0 & 0 \\ 0 & h_q & 0 & 0 \\ 0 & 0 & h_n & 0 \\ 0 & 0 & 0 & h_p \end{bmatrix};$$
$$A = \begin{bmatrix} T_N & T_N & T_{Ni} & 0 \\ g_m \times T_P & g_q \times T_P & 0 & T_{Pi} \\ 1 & \text{Nmax} & 0 & 0 \end{bmatrix}; b = \begin{bmatrix} \text{Ntar} \times \text{AeqN} \\ \text{Ptar} \times \text{AeqP} \\ \text{N0} \times \text{Nmax} \end{bmatrix};$$
$$LB = \; 0 \quad 0 \quad 0 \quad 0 \; ; UB = \; \infty \quad \text{N0} \quad \text{N0i} \times \text{Nmaxi} \quad \text{P0i} \times \text{Pmaxi} \tag{5.11}$$

5.1 Upscaling to multiple sectors and regions

Extending the model from 1 farming sector, 1 wastewater treatment plant and wetlands, to the regional level, leads to 8 farm-sectors where nutrients can be reduced by measures as well as quota restrictions. We aggregate all regional wastewater treatment plants into one single representative wastewater treatment plant, which can target N as well as P separately. Finally there is 1 variable for the reduction in nutrient loads by the construction of wetlands in the entire river basin. Hence, N_M and P_Q become both 1x8 vectors, while N, P and n stay single variables. This results in 2x9+1 relevant sectors. Therefore, vector X in the problem with one region can be stated as follows[4]:

$$X^T = \begin{bmatrix} N_{M_1} & \cdots & N_{M_8} & N & N_{Q_1} & \cdots & N_{Q_8} & P & n \end{bmatrix} \tag{5.12}$$

Dividing the basin into regions (r), leads to 8xr farm-sectors where nutrients can be reduced by measures and quota restrictions. In each region we distinguish, as before, one wastewater treatment plant, which can target N and P separately. Finally there is 1 variable for the reduction in nutrient loads by the construction of wetlands in the entire basin. Hence, N_M and P_Q becomes both a 1x8xr vector, N and P become both a 1xr vector, while n remains one single variable. This results in 2x9xr+1 relevant sectors. Therefore, vector X in the problem with multiple regions can be stated as follows:

$$\begin{aligned} X^T = [& {N_{M_1}}^1 \; \cdots \; {N_{M_8}}^1 \; N^1 \; {N_{M_1}}^2 \; \cdots \; {N_{M_8}}^2 \; N^2 \\ & \cdots \; \cdots \; \cdots \; \cdots \; {N_{M_1}}^r \; \cdots \; {N_{M_8}}^r \; N^r \\ & {N_{Q_1}}^1 \; \cdots \; {N_{Q_8}}^1 \; P^1 \; {N_{Q_1}}^2 \; \cdots \; {N_{Q_8}}^2 \; P^2 \\ & \cdots \; \cdots \; \cdots \; \cdots \; {N_{Q_1}}^r \; \cdots \; {N_{Q_8}}^r \; P^r \; n] \end{aligned} \tag{5.13}$$

Figure 5.2 gives an illustration of the CENER model with multiple regions and the required changes.

4 Expanding *f*, *H*, *A*, *b*, *LB*, and *UB* is straightforward and not presented here.

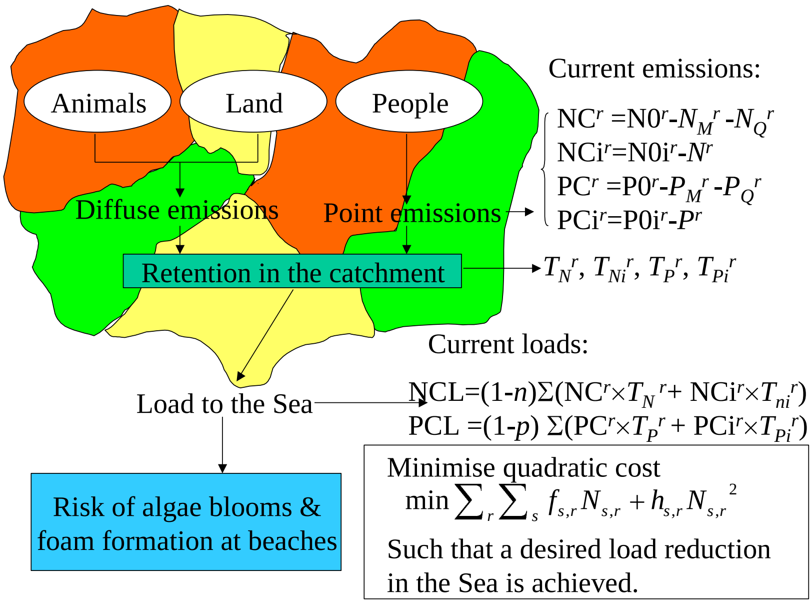


Figure 5.2 5.3 CENER model; the catchment consists of multiple regions.

The cost minimisation problem is implemented as a quadratic programming problem with the mathematical programming language MATLAB.

6. Output and interpretation of model results

The CENER model, as described in Chapter 5, is used to calculate the result for the case where the load of N and P is reduced by 50% with respect to 1985 levels of emissions. We have chosen for this case as it corresponds to the short-term target of the North Sea conference. The results are presented for four situations, namely for the Rhine and the Elbe catchment, with and without wetlands. The distinction between with and without wetlands is taken to shed light on the debate on the viability of including wetlands as an option for nutrient emission reduction.

The solution of the model consists of a vector *X*, representing the optimal sectoral emission reduction levels in kgs. From this vector, the sectoral reduction percentages for total N (Ntot) and total P (Ptot) can be derived (which is done in the MATLAB code). Furthermore, we distinguish between the required reduction percentages for measures (Nmeas) and quota restrictions (Nquota=Pquota) at diffuse sources. The reduction percentage of P through measures (Pmeas) can be derived from the initial emissions in the Appendix and the dependence on Nmeas via Equation (4.5) this is not presented in the Appendix. Finally, some additional information is calculated, namely the retention percentages in wetlands, the reduction cost divided into costs for diffuse and point sources and wetland construction, and the final reduction fraction in the load to the coastal seas. The appendix presents the detailed sectoral results for the four situations, the Rhine and the Elbe catchment, with and without wetlands in Table A1.1–Table A1.4.

Besides, the detailed model result, it is also possible to aggregate the numbers into regional reduction percentages. The aggregated results are presented in Table 6.1 to Table 6.4, respectively for the Elbe and Rhine basin and graphically in Figure 6.1.

Table 6.1 Cost-optimal reduction percentages for reaching the target of 50% N and P reduction ***without*** *wetlands in the* ***Elbe*** *Basin.*

[%]	Ntot	Nmeas	Nquota	Ptot	Pmeas	Pquota	Nwwtp	Pwwtp
1. Oberelbe	59.85	59.83	0.02	3.59	0.75	0.02	0.00	71.19
2. Vlatava/Moldau	60.56	60.54	0.02	3.42	0.71	0.02	0.00	71.19
3. Ohre/Eger	61.68	61.66	0.02	3.15	0.65	0.02	0.00	71.19
4. Saale	62.76	62.76	0.00	1.85	0.38	0.00	0.00	68.62
5.Mulde Schwarze Elster	66.43	66.43	0.00	2.36	0.49	0.00	0.00	84.63
6. Havel	61.03	61.02	0.00	1.28	0.26	0.00	0.00	67.33
7. Middle Elbe	66.33	66.32	0.00	2.26	0.47	0.00	0.00	76.29
8. Tideelbe	55.48	55.48	0.00	3.83	0.81	0.00	0.00	73.75

Note: Ntot (Nquota + (100–Nquota)/100) and Ptot are the reduction percentages of respectively total N and total P at farms. Nmeas and Pmeas represent the respectively needed N and P reduction with measures at farms, and Quota shows the percentage of farms that needs to be closed. Nwwtp and Pwwtp are the reduction percentages of respectively N and P via wastewater treatment.

Table 6.1 suggests that in order to achieve the 50% N and P reduction in the Elbe basin without wetlands, no additional effort for reducing N at wastewater treatment plants is required. P has to be reduced by 67–85% at wastewater treatment plants and N has to be reduced by 55–66% through measures and 0–0.02% quota restrictions are required.

*Table 6.2 Cost-optimal reduction percentages for reaching the target of 50% N and P reduction **with** wetlands in the **Elbe** Basin.*

[%]	Ntot	Nmeas	Nquota	Ptot	Pmeas	Pquota	Nwwtp	Pwwtp
1. Oberelbe	58.26	58.24	0.02	3.48	0.73	0.02	0.00	70.54
2. Vlatava/Moldau	58.94	58.92	0.02	3.31	0.69	0.02	0.00	70.54
3. Ohre/Eger	60.02	60.00	0.01	3.04	0.63	0.01	0.00	70.54
4. Saale	61.06	61.06	0.00	1.77	0.37	0.00	0.00	68.01
5.Mulde Schwarze Elster	66.17	66.17	0.00	2.27	0.47	0.00	0.00	83.73
6. Havel	59.39	59.38	0.00	1.23	0.25	0.00	0.00	66.75
7. Middle Elbe	66.08	66.07	0.00	2.18	0.45	0.00	0.00	75.55
8. Tideelbe	54.32	54.32	0.00	3.71	0.78	0.00	0.00	73.05

Table 6.2 shows again that no additional effort for reducing N at wastewater treatment plants is required. The percentages at farms and wastewater treatment plants do not go down substantially as wetlands can only retain 3% of N and 2% of P.

*Table 6.3 Cost-optimal reduction percentages for reaching the target of 50% N and P reduction **without** wetlands in the **Rhine** Basin.*

[%]	Ntot	Nmeas	Nquota	Ptot	Pmeas	Pquota	Nwwtp	Pwwtp
1. Alp Rhine	52.72	52.69	0.03	10.79	2.38	0.03	39.09	51.71
2. High Rhine	62.09	62.07	0.03	9.60	2.07	0.03	48.53	85.70
3. Moselle/Sarre	70.21	70.20	0.01	1.66	0.34	0.01	33.57	71.69
4. Upper Rhine	69.11	69.11	0.01	2.71	0.56	0.01	34.00	68.20
5. Neckar	67.55	67.54	0.01	5.38	1.14	0.01	35.17	65.08
6. Main	67.92	67.92	0.01	3.91	0.82	0.01	28.48	56.26
7. Middle Rhine	67.74	67.73	0.01	5.31	1.12	0.01	33.21	65.17
8. Lower Rhine	57.92	57.91	0.01	8.00	1.77	0.01	26.14	38.53
9. Rhine Delta	28.30	28.29	0.02	2.41	0.53	0.02	0.00	0.00

Table 6.3 shows that the reduction percentages in the Rhine basin are substantially lower in the Netherlands. Table 6.3 suggests, for the other 8 subcatchments of the Rhine, an additional effort for reducing N at wastewater treatment plants between 26–49% in the case without wetlands. Furthermore, P has to be reduced by 39–86% at wastewater treatment plants and N has to be reduced by 53–70% through measures and 0.01–0.03% quota restrictions are required.

Table 6.4 Cost-optimal reduction percentages for reaching the target of 50% N and P reduction ***with*** *wetlands in the* ***Rhine*** *Basin.*

[%]	Ntot	Nmeas	Nquota	Ptot	Pmeas	Pquota	Nwwtp	Pwwtp
1. Alp Rhine	37.68	37.67	0.01	3.73	0.82	0.01	0.00	37.23
2. High Rhine	47.84	47.83	0.01	3.58	0.77	0.01	0.00	75.88
3. Moselle/Sarre	60.24	60.23	0.00	0.57	0.12	0.00	0.00	55.56
4. Upper Rhine	59.22	59.21	0.00	0.94	0.19	0.00	0.00	52.36
5. Neckar	56.25	56.25	0.00	1.69	0.36	0.00	0.00	49.50
6. Main	55.65	55.65	0.00	1.53	0.32	0.00	0.00	41.41
7. Middle Rhine	57.10	57.10	0.00	1.96	0.41	0.00	0.00	49.58
8. Lower Rhine	42.35	42.35	0.01	3.46	0.77	0.01	0.00	25.12
9. Rhine Delta	19.24	19.23	0.01	1.71	0.38	0.01	0.00	0.00

Table 6.4 shows the result when wetlands retain 29% of N and 21% of P. Then, it is no longer necessary to reduce N at wastewater treatment plants. P has to be reduced by 25–76% at wastewater treatment plants and N has to be reduced by 38–60% through measures and 0–0.01% quota restrictions are required.

From Table 6.1–Table 6.4, we can see that the quota restrictions are only used to a very limited extend. This is a very expensive way of achieving a reduction.

Let us now turn to raised question in the introduction with respect to costs. Table 6.5 presents the load reduction through wetlands, the reduction to the load to the North Sea, the costs for reducing diffuse and point emissions and the costs for constructing wetlands.

Table 6.5 The ***calculated*** *total load reduction through wetlands, the resulting loads to the North Sea and total costs.*

	Elbe		Rhine	
	Without wetlands	With wetlands	Without wetlands	With wetlands
Nwetland	0.00	3.04	0.00	28.61
Pwetland	0.00	2.28	0.00	21.43
Nfinal	50.00	50.00	50.00	50.00
Pfinal	50.00	50.00	50.00	50.00
Measures at farm	330.13	315.23	620.50	285.43
Closing farms	0.04	0.04	0.18	0.03
N measures at WWTPs	0.00	0.00	291.22	0.00
P measures at WWTPs	275.29	267.75	226.32	158.74
Wetland construction	0.00	20.81	0.00	396.91
Total cost (M€)	605.46	603.84	1138.22	841.11

Note: Nwetland and Pwetland are the percentages of N and P retention by wetlands. Nfinal and Pfinal represent the reduction percentages in the N and P load.

Table 6.5 shows, as expected, that there is no load reduction through wetlands in the case where no additional wetlands are constructed and that the reduction in the load to the North Sea is 50% N and P in all four cases.

Furthermore, the reduction costs are 605 million euro for the Elbe basin without using wetlands and 604 million euro for the Elbe basin with using wetlands, 1138 million euro for the Rhine basin without using wetlands and 841 million euro for the Rhine basin with using wetlands. The outcome of the model suggests that it is cost effective to devote 4.0% of arable land to wetlands in the Rhine basin, while the model suggests only a conversion of 0.3% of arable land to wetlands in the Elbe basin. Hence, there is an interesting result: in the Rhine basin it is cheaper to achieve the load reduction with wetlands, while this not the case in the Elbe basin.

Table 2.1 and Table 2.3 can explain why wetlands are not a cost effective option in the Elbe basin. These tables show that there is more arable land in the Elbe basin, while the numbers of animals and inhabitants are substantially lower in the Elbe basin. This reduces the cost of diffuse emission reduction to such an extent that wetlands are no longer an attractive option. Besides, the costs of wetlands construction in the Elbe basin are possibly underestimated, because in order to obtain the same levels of reduction in the Rhine basin (what we have assumed here) even more land has to be devoted to wetlands (as the total amount of arable land is larger).

There are many assumptions in the CENER model. In that respect the result in Table 6.5 is only an approximation of the cost optimal outcome. In order to verify the error of the model, the solution is re-substituted into the model without the following assumptions:

- Costs increase quadratically in the amount of reduction at the source (error in costs).
- Measures at pig farms and wetland construction reduce N and P in fixed proportions (error in P reduction).[5]
- Linearisation of the reduction through wetlands (error in N reduction).

*Table 6.6 The **actual** total load reduction through wetlands, the resulting loads to the North Sea, and total costs.*

	Elbe		Rhine	
	Without wetlands	With wetlands	Without wetlands	With wetlands
Nwetland	0.00	3.04	0.00	28.61
Pwetland	0.00	1.97	0.00	19.73
Nfinal	50.00	50.56	50.00	50.10
Pfinal	49.26	49.78	49.71	49.86
Measures at farm	334.08	323.91	625.76	322.84
Closing farms	1.71	1.66	3.66	1.56
N measures at WWTPs	0.00	0.00	292.28	0.00
P measures at WWTPs	271.03	264.05	304.66	177.39
Wetland construction	0.00	30.04	0.00	370.43
Total cost (M€)	606.82	619.66	1226.36	872.23

Note: Nwetland and Pwetland are the percentages of N and P retention by wetlands. Nfinal and Pfinal represent the reduction percentages in the N and P load.

Table 6.6 shows that in case the reduction percentages of the Appendix are implemented that the reduction in the P load will be somewhat lower and the reduction in the N load

[5] There is no error in assuming that quota restrictions reduce N and P in fixed proportions.

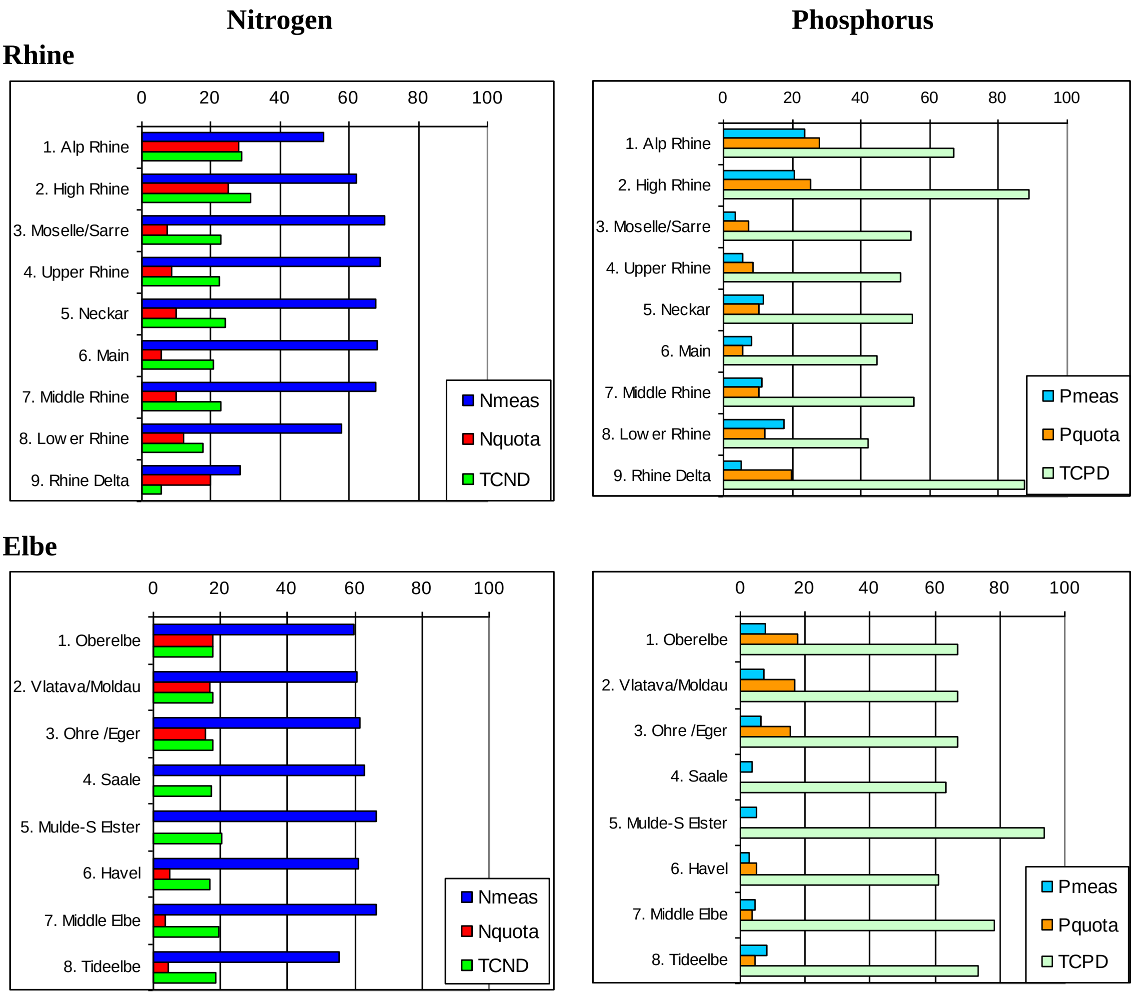
somewhat higher, but these differences are marginal. The error in the costs, due to the quadratic approximation in the model is low enough to be acceptable. The cost difference in the Elbe basin with using wetlands as compared to without using wetlands suggest that the inclusion of wetlands does not lower the cost for reducing nutrients.

In the introduction of this report we raised the issue that it may be substantially cheaper to regionally differentiate emission reduction. To compare the results, the cost of a “flat rate reduction” has been calculated too. This is, however, not a trivial task, as it is not a priori clear, what a flat rate reduction means when wetlands are also allowed for. In order to stay close to the derived solution, we assume that the same amount of wetlands is constructed as in the cost-optimal case. Under this assumption, the remaining reduction has to be achieved in the same fixed proportions by wastewater treatment plants and farms. This means, for example, for the case of the Rhine basin that 30% (=1-0.5/(1-0.29)) N and 36% (=1-0.5/(1-0.21)) P has to be reduced by all wastewater treatment plants and farms in all regions. Wastewater treatment plants have only one option, while farms have more flexibility to reduce, as they have the option to choose between various farm types and between quota restrictions and measures. Nevertheless, they all have to reduce at the same regional level as the wastewater treatment plants.

Under these assumptions, the total costs for achieving the 50% reduction target increases with factor 9 to 5423 million euros in the case of a “flat rate reduction” in the Elbe basin. The total costs for achieving the 50% reduction target increases by factor 8, to 6758 million euros, in the case of a “flat rate reduction” with wetlands in the Rhine basin. This is due to the need for quota restrictions at farms, for reaching the required reduction. This is a very expensive way of reducing nutrients. There are not enough options to reduce P via (technical) measures at farms. Moreover, 17–46% quota restrictions are needed in the Elbe basin and 19–29% in the Rhine basin.

For interpreting the differences in the results between the Rhine and Elbe basin, it is also useful to compare the N and P reduction percentages with the transport coefficients. Such a comparison is presented graphically in Figure 6.1 for diffuse emissions. Figure 6.1 consists of four bar charts, distinguishing between the Rhine and Elbe basin, and N and P emissions. For each subcatchment, three values are plotted: emission reduction percentages through measures and quota restrictions at farms, and the transport coefficients for diffuse sources. The quota restrictions and transport coefficients are rescaled in order to make the relative differences more apparent.

Figure 6.2 consists of four bar charts, distinguishing between the Rhine and Elbe basin, and N and P emissions. For each subcatchment, two values are plotted: emission reduction percentages through measures at wastewater treatment plants and the transport coefficients for point sources. The transport coefficients are rescaled in order to make the relative differences more apparent.



Note: Nitrogen emission reduction percentages through measures (Nmeas) and quota restrictions (Nquota (value times 1000)) at farms, and transport coefficients (TCND (value times 100)).

Note: Phosphorus emission reduction percentages through measures (Pmeas) and quota restrictions (Pquota (value times 1000)) at farms, and transport coefficients (TCND (value times 10000)).

Figure 6.1 Graphical representation of the regionally differentiated reduction percentages at farms to reach a load reduction of 50% N and P from the Rhine and Elbe basin without using wetlands.

For interpreting the results in Figure 6.1, let us first consider nitrogen reduction in the Rhine basin. Here we see the highest reduction percentages through measures in the middle part of the Rhine (Moselle/Sarre, Upper Rhine, Neckar, Main and Middle Rhine), while the transport coefficients are high upstream in the Alps, intermediate midstream in France/Germany and low downstream in the Netherlands. In order to find an explanation for this result, we need to consult Table 2.3 and Tabel 4.1. Close inspection of Tabel 2.3 tells us that the middle of the Rhine is dominated by arable farming and that the numbers of animals per ha of arable land are low here. The opposite is true for Alp Rhine, High Rhine, Lower Rhine and Rhine Delta. Furthermore, Table 4.1 shows that about 90% of nitrogen can be reduced through measures at arable land, while only 70% can be reduced through measures at animal farms. Hence, a lower (higher) animal-land ratio can explain a higher (lower) level of emission reduction through measures at farms.

The variation in phosphorus emission reduction through measures at farms can only be explained by inspecting the number of pigs in the related subcatchments from Table 2.3. Table 2.3 shows that there are more pigs per subcatchment upstream than midstream, while the number of pigs downstream are the highest. As a result, the highest phosphorus reduction with measures at farms is found in the Alp and High Rhine in Switzerland and in the Lower Rhine in Germany. However, one question remains: why do we find a low P reduction through measures in the Netherlands, while the transport coefficient for P is the highest? The answer to this question can be found by looking into the reduction of N emissions. In order to reduce P, N has to be reduced too. However, the transport of N in the Netherlands 4 times lower than in the rest of the Rhine basin and it is therefore not very cost-effective to reduce N and, hence, to reduce P.

The level of phosphorus reduction through quota measures clearly follows the level of transport coefficients. The highest quota reductions are found in Switzerland and the Netherlands, where also the transport of P is the highest in those regions.

As explained before, there is much less variation in the transport coefficients for the Elbe basin. As a result, the reduction percentages are quite evenly distributed over the subcatchments.

Nitrogen reduction through measures at farms in the Elbe basin generally follows the pattern where a higher transport coefficient leads to a higher reduction percentage and vice versa. There is, however, one exception, namely in Tideelbe, where we would have expected a higher reduction percentage, due to the relative high transport coefficient. The number of animals and the amount of arable land indicate a high number of animals per ha, which –as concluded before– reduces the potential of measures to reduce nitrogen.

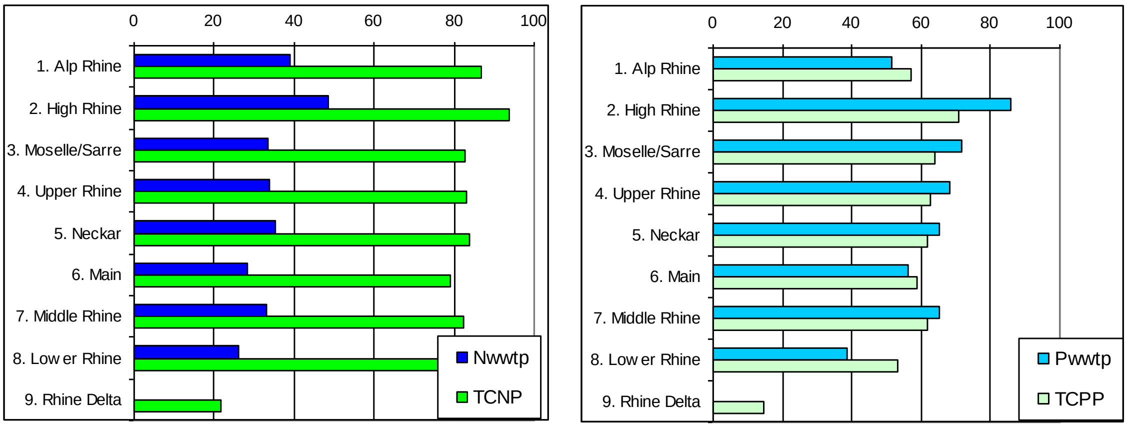
Phosphorus reduction through quota restrictions at farms in the Elbe basin can be grouped into three levels, namely 0.015 % upstream in Czech Republic, 0.0005% midstream in Saale and Mulde Schwarze Elster, and 0.005% downstream in Havel, Middle Elbe and Tideelbe. A close inspection of Table 2.1, shows that the number of animals per land is the lowest midstream, which is makes it the cheapest to reduce through measures, rather than using quota restrictions.

Besides, we need to keep in mind that the levels of quota restrictions are very low. Because of that the level of substantial emission reduction through measures at farms is more important for the Elbe and Rhine basin.

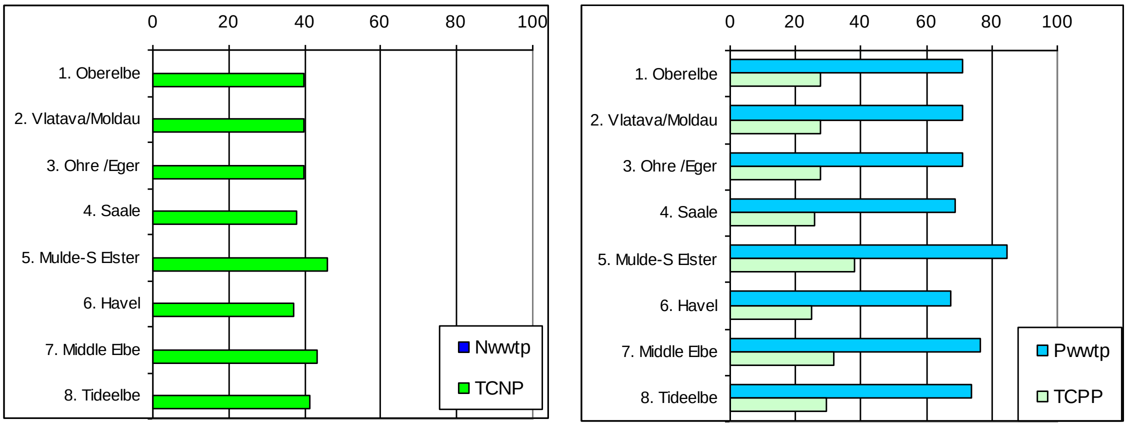
Finally, Figure 6.1 shows that the option to cost-optimally reduce phosphorus through measures at farms is substantially lower in the Elbe catchment, than in the Rhine catchment. This is most clearly caused by the substantial lower number of pigs in the Elbe catchment than in the Rhine catchment (these numbers are presented in Table 2.1 and Table 2.3).

Nitrogen **Phosphorus**

Rhine



Elbe



Note: Nitrogen emission reduction percentages through measures (Nwwtp) at wastewater treatment plants, and transport coefficients (TCNP (value times 100)).

Note: Phosphorus emission reduction percentages through measures (Pwwtp) at wastewater treatment plants, and transport coefficients (TCPP (value times 100)).

Figure 6.2 Graphical representation of the regionally differentiated reduction percentages at wastewater treatment plants to reach a load reduction of 50% N and P from the Rhine and Elbe basin without using wetlands.

It is quite easy to interpret nutrient emission reduction as wastewater treatment plants. In most cases a higher transport coefficient leads to a higher emission reduction percentage. As the costs of wastewater treatment are quite substantial, the restricting factor is clearly the amount of nutrient transport. For instance, since the transport coefficients are high upstream in the Alps, intermediate midstream in France/Germany and low downstream in the Netherlands, the optimal solution also suggests to take high quota restrictions and wastewater treatment in the Alps, intermediate in Germany and low in the Netherlands.

Figure 6.2 also shows that about 70% phosphorus is reduced in the cost-optimal situation in the Rhine and Elbe basin, while 30% nitrogen is reduced in the Rhine basin and 0% in the Elbe basin. This shows that phosphorus reduction is relatively cheaper at wastewater treatment plants, while nitrogen reduction is relatively cheaper at farms.

7. Conclusions

This report has tried to address the following the research question: what are the characteristics of a cost-effective solution to achieve a given target on nutrient loads? More specifically, what is the sectoral distribution of reduction targets in the cost-optimal solution and what is the cost difference with the flat-rate reduction targets? To answer these questions, this report has calculated a regionally differentiated cost efficient reduction of nutrients for the Rhine and Elbe basin. A model has been set up which represents a situation where nutrient emissions originate from three drivers, namely animals, land and people. A large fraction of these emissions are retained in the catchment, which is considered the fourth driver. Only a fraction of the emitted nutrients ultimately reach the sea, which possibly leads to negative impacts like algae blooms and foam formation at beaches.

The model uses quantified information on the number of animals at farms, hectares of arable land and inhabitant equivalents at the subcatchment level. From that, the emissions are calculated via per head or per hectare emission factors. These emissions are reduced in the catchment via linear regionally different transport coefficients, from which the load to the North Sea is derived. Furthermore, estimates of the marginal costs to reduce diffuse and point emissions and/or increasing retention via wetlands are an input into the model.

The CENER model is based on a number of assumptions:

1. Transport of nutrients from the source to the sea are assumed to be a linear fraction;
2. Nitrogen and phosphorus are assumed to be reduced in fixed proportions;
3. Costs are upscaled to the catchment level from a detailed study on the Netherlands;
4. Costs depend linearly on the number of animals, amount of land and number of inhabitants in the catchment;
5. Costs increase quadratically in the amount of reduction at the source.

The solution of the model is recalculated without the second and the fifth assumption. This only leads to a marginal difference in the final load reduction and the total cost of implementing the reduction programme. Hence, the CENER model is quite robust.

The results of the model show that the quota restrictions are very low (only 1–3 ‰), as this is a very expensive way of achieving a reduction.

The regional differences in reduction percentages can be explained by a number of factors. First, a higher transport coefficient leads to a higher reduction percentage. For instance, if we compare the transport coefficients with the reduction percentages in the Rhine basin, we find a correspondence. Namely, as the transport coefficients are high upstream in the Alps, intermediate midstream in France/Germany and low downstream in the Netherlands, the optimal solution also suggests to undertake high wastewater treatment in the Alps, intermediate in Germany and low in the Netherlands.

Second, we have a difference in the animal-land ratio in various subcatchments. On average about 70% of nitrogen emissions can be by measures at animal farms, while about

90% at arable farms. Hence, a lower (higher) animal-land ratio can explain a higher (lower) level of emission reduction through measures at farms.

Third, in some instance we find that in order to reduce phosphorus, nitrogen has to be reduced too. For instance, we have a high transport coefficient for phosphorus in the Netherlands, but we still find a low reduction percentage. However, the transport of N in the Netherlands 4 times lower than in the rest of the Rhine basin and it is therefore not very cost-effective to reduce N and, hence, to reduce P.

Fourth, the variation in phosphorus emission reduction through measures at farms is explained by the variation in the numbers of pigs in the subcatchments (this is the only farm type where phosphorus can be reduced by measures). There are more pigs per subcatchment upstream than midstream, while the number of pigs downstream is the highest; the highest phosphorus reduction with measures at farms is found in the Swiss dominated Alp and High Rhine and the German district of the Lower Rhine. As the number of pigs in the Elbe catchment is about half of the number of pigs in the Rhine catchment, the option to cost-optimally reduce phosphorus through measures at farms is substantially lower in the Elbe catchment.

Fifth, the transport coefficients for the Elbe basin show much less variation than the transport coefficients in the Rhine basin. As a result there is much less variation in the emission reduction percentages.

The most striking result is, however, the difference in the total cost. In the Elbe basin there is no cost difference in achieving a load reduction with wetlands, while it is cheaper in the Rhine basin to include wetlands as an option for nutrient reduction. An explanation is, for instance, that there is more arable land in the Elbe basin, while the numbers of animals and inhabitants are substantially lower in the Elbe basin. This reduces the cost of diffuse emissions to such an extent that wetlands are no longer an attractive option. Besides, the costs of wetlands construction in the Elbe basin are possibly underestimated, because in order to obtain the same levels of reduction in the Rhine basin (what we have assumed here) even more land has to be devoted to wetlands (as the total amount of arable land is larger).

One of our research questions was to compare the total cost of the flat rate solution with the total costs of the cost-effective solution. To establish this result, we have assumed that the same amount of wetlands is constructed in the flat-rate solution as in the cost-effective solution. Under this assumption, the remaining reduction has to be achieved in the same fixed proportion by wastewater treatment plants and farms. The cost for the Rhine basin increase with factor 8 from 841 million euro to 6758 million euro, while the costs for the Elbe basin increase with factor 9 from 604 million euro to 5423 million euro. This shows that it is really worth the effort to strive for the cost-effective solution.

Research on finding cost-optimal solutions for water quality problems in the coast by measures in the catchment can be continued in various directions. For the Rhine and Elbe, it would be useful to improve the estimates of the marginal costs. Furthermore, the estimates of nutrient transport and the regional differences could be improved upon. In a wider perspective it could be interesting to apply the model to other catchment-coast systems as well. This report can serve as guiding manual for collecting the right kind of information. This report serves as a motivation for undertaking such research by showing that location and local conditions can make a great deal of difference.

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Appendix I. Detailed model result – sectoral reduction percentages and initial emissions

Table AI.1 Total required nitrogen emission reduction.

	Elbe			Rhine		
	Without wet-lands [%]	With wet-lands [%]	InitEM [tonnes N]	Without wet-lands [%]	With wet-lands [%]	InitEM [tonnes N]
Ntot01	4.19	4.06	215	13.56	5.80	70
Ntot02	36.68	36.62	112	41.04	37.43	37
Ntot03	62.41	61.85	13923	95.10	69.34	2749
Ntot04	79.76	76.91	27222	84.60	84.60	5375
Ntot05	28.25	28.06	4531	41.67	30.55	10694
Ntot06	22.85	22.55	6001	44.02	26.49	14164
Ntot07	6.48	5.88	1872	25.41	2.40	2419
Ntot08	31.65	30.99	3471	61.14	31.51	2718
Ntot09wwtp	0.00	0.00	4388	39.09	0.00	8617
Ntot10	4.19	4.06	407	14.68	6.28	99
Ntot11	36.68	36.62	213	41.57	37.66	52
Ntot12	62.41	61.85	28361	95.10	71.42	8400
Ntot13	79.76	76.91	55452	84.60	84.60	16424
Ntot14	28.25	28.06	8593	43.28	31.25	14177
Ntot15	22.85	22.55	11381	46.56	27.58	18777
Ntot16	6.48	5.88	3550	29.81	4.83	3038
Ntot17	31.65	30.99	6583	66.20	34.06	3689
Ntot18wwtp	0.00	0.00	8323	48.53	0.00	9211
Ntot19	4.19	4.06	118	10.64	4.55	53
Ntot20	36.68	36.62	62	39.69	36.85	28
Ntot21	62.41	61.85	9282	90.17	63.97	19275
Ntot22	79.76	76.91	18148	84.60	84.60	37687
Ntot23	28.25	28.06	2500	37.49	28.77	11063
Ntot24	22.85	22.55	3311	37.43	23.67	14652
Ntot25	6.48	5.88	1033	16.24	0.00	1063
Ntot26	31.65	30.99	1915	49.63	26.37	1144
Ntot27wwtp	0.00	0.00	2421	33.57	0.00	10619
Ntot28	4.07	3.94	12	10.38	4.44	52
Ntot29	36.63	36.57	6	39.57	36.80	27
Ntot30	61.90	61.35	28103	89.05	63.50	15539
Ntot31	77.17	74.40	54947	84.60	84.60	30382
Ntot32	28.07	27.89	5927	37.12	28.61	8881
Ntot33	22.58	22.29	7849	36.84	23.42	11763
Ntot34	5.49	4.91	2582	15.32	0.00	1477
Ntot35	30.74	30.11	3053	48.53	25.84	1611
Ntot36wwtp	0.00	0.00	11019	34.00	0.00	10584
Ntot37	4.89	4.74	8	11.29	4.83	44
Ntot38	37.01	36.94	4	39.99	36.98	23

	Elbe			Rhine		
	Without wetlands [%]	With wetlands [%]	InitEM [tonnes N]	Without wetlands [%]	With wetlands [%]	InitEM [tonnes N]
Ntot39	65.44	64.77	18595	92.95	65.17	11296
Ntot40	84.60	84.60	36357	84.60	84.60	22086
Ntot41	29.25	29.03	5390	38.42	29.16	7584
Ntot42	24.44	24.09	7138	38.89	24.30	10045
Ntot43	13.24	12.49	1737	18.15	0.00	2366
Ntot44	37.65	36.85	1693	52.10	27.43	2232
Ntot45wwtp	0.00	0.00	8701	35.17	0.00	11876
Ntot46	3.97	3.85	68	9.58	4.10	54
Ntot47	36.58	36.52	36	39.19	36.64	29
Ntot48	61.48	60.94	16853	85.61	62.02	22948
Ntot49	75.05	72.35	32951	84.60	77.80	44870
Ntot50	27.93	27.75	4134	35.97	28.12	11799
Ntot51	22.36	22.07	5475	35.03	22.64	15628
Ntot52	4.77	4.21	1369	12.64	0.00	2987
Ntot53	30.06	29.44	1270	45.26	24.32	4139
Ntot54wwtp	0.00	0.00	13603	28.48	0.00	12159
Ntot55	4.63	4.48	45	10.66	4.56	39
Ntot56	36.89	36.82	24	39.70	36.86	20
Ntot57	64.28	63.66	17073	90.27	64.02	9684
Ntot58	84.60	84.60	33381	84.60	84.60	18934
Ntot59	28.87	28.66	4533	37.52	28.78	5856
Ntot60	23.83	23.50	6004	37.48	23.69	7756
Ntot61	9.72	9.04	1548	16.35	0.00	1618
Ntot62	34.69	33.96	1869	49.75	26.44	2209
Ntot63wwtp	0.00	0.00	3338	33.21	0.00	12253
Ntot64	4.45	4.31	47	8.18	3.50	97
Ntot65	36.80	36.74	24	38.54	36.36	51
Ntot66	63.51	62.91	10368	79.58	59.44	13206
Ntot67	84.60	82.26	20273	84.60	64.86	25821
Ntot68	28.61	28.41	7577	33.96	27.26	9297
Ntot69	23.43	23.11	10036	31.86	21.29	12314
Ntot70	8.33	7.69	1578	8.40	0.00	5684
Ntot71	33.40	32.70	3215	39.84	21.96	7962
Ntot72wwtp	0.00	0.00	9124	26.14	0.00	28512
Ntot73				2.58	1.10	993
Ntot74				35.93	35.25	521
Ntot75				55.47	49.12	15108
Ntot76				44.93	13.11	29540
Ntot77				25.93	23.82	33291
Ntot78				19.20	15.87	44093
Ntot79				0.00	0.00	10753
Ntot80				20.21	14.36	11753
Ntot81wwtp				0.00	0.00	24470

Note: InitEM are the initial emissions of N. Ntot is the reduction percentages of total N.

Table AI.2 Total required phosphorus emission reduction.

	Elbe			Rhine		
	Without wetlands [%]	With wetlands [%]	InitEM [tonnes P]	Without wetlands [%]	With wetlands [%]	InitEM [tonnes P]
Ptot01	0.00	0.00	0	0.00	0.00	0
Ptot02	0.00	0.00	0	0.00	0.00	0
Ptot03	0.00	0.00	5153	0.00	0.00	1018
Ptot04	0.00	0.00	3029	0.00	0.00	598
Ptot05	0.00	0.00	925	0.00	0.00	2183
Ptot06	0.00	0.00	1265	0.00	0.00	2985
Ptot07	9.86	8.94	733	38.63	3.65	947
Ptot08	40.84	40.00	878	78.89	40.66	687
Ptot09wwtp	71.19	70.54	423	51.71	37.23	831
Ptot10	0.00	0.00	0	0.00	0.00	0
Ptot11	0.00	0.00	0	0.00	0.00	0
Ptot12	0.00	0.00	10498	0.00	0.00	3109
Ptot13	0.00	0.00	6171	0.00	0.00	1828
Ptot14	0.00	0.00	1754	0.00	0.00	2894
Ptot15	0.00	0.00	2398	0.00	0.00	3957
Ptot16	9.86	8.94	1389	45.32	7.34	1189
Ptot17	40.84	40.00	1665	85.42	43.95	933
Ptot18wwtp	71.19	70.54	802	85.70	75.88	888
Ptot19	0.00	0.00	0	0.00	0.00	0
Ptot20	0.00	0.00	0	0.00	0.00	0
Ptot21	0.00	0.00	3436	0.00	0.00	7135
Ptot22	0.00	0.00	2020	0.00	0.00	4194
Ptot23	0.00	0.00	510	0.00	0.00	2258
Ptot24	0.00	0.00	698	0.00	0.00	3088
Ptot25	9.86	8.94	404	24.68	0.00	416
Ptot26	40.84	40.00	484	64.04	34.02	289
Ptot27wwtp	71.19	70.54	233	71.69	55.56	1024
Ptot28	0.00	0.00	0	0.00	0.00	0
Ptot29	0.00	0.00	0	0.00	0.00	0
Ptot30	0.00	0.00	10402	0.00	0.00	5752
Ptot31	0.00	0.00	6115	0.00	0.00	3381
Ptot32	0.00	0.00	1210	0.00	0.00	1813
Ptot33	0.00	0.00	1654	0.00	0.00	2479
Ptot34	8.35	7.47	1011	23.29	0.00	578
Ptot35	39.67	38.85	772	62.63	33.35	407
Ptot36wwtp	68.62	68.01	1062	68.20	52.36	1020
Ptot37	0.00	0.00	0	0.00	0.00	0
Ptot38	0.00	0.00	0	0.00	0.00	0
Ptot39	0.00	0.00	6883	0.00	0.00	4181
Ptot40	0.00	0.00	4046	0.00	0.00	2458
Ptot41	0.00	0.00	1100	0.00	0.00	1548
Ptot42	0.00	0.00	1504	0.00	0.00	2117
Ptot43	20.14	18.99	680	27.60	0.00	926

	Elbe			Rhine		
	Without wet-lands [%]	With wet-lands [%]	InitEM [tonnes P]	Without wet-lands [%]	With wet-lands [%]	InitEM [tonnes P]
Ptot44	48.59	47.56	428	67.23	35.40	564
Ptot45wwtp	84.63	83.73	839	65.08	49.50	1145
Ptot46	0.00	0.00	0	0.00	0.00	0
Ptot47	0.00	0.00	0	0.00	0.00	0
Ptot48	0.00	0.00	6238	0.00	0.00	8494
Ptot49	0.00	0.00	3667	0.00	0.00	4993
Ptot50	0.00	0.00	844	0.00	0.00	2409
Ptot51	0.00	0.00	1154	0.00	0.00	3293
Ptot52	7.25	6.40	536	19.21	0.00	1169
Ptot53	38.79	37.99	321	58.40	31.39	1047
Ptot54wwtp	67.33	66.75	1311	56.26	41.41	1172
Ptot55	0.00	0.00	0	0.00	0.00	0
Ptot56	0.00	0.00	0	0.00	0.00	0
Ptot57	0.00	0.00	6320	0.00	0.00	3585
Ptot58	0.00	0.00	3715	0.00	0.00	2107
Ptot59	0.00	0.00	925	0.00	0.00	1195
Ptot60	0.00	0.00	1265	0.00	0.00	1634
Ptot61	14.77	13.74	606	24.86	0.00	633
Ptot62	44.76	43.82	473	64.20	34.11	559
Ptot63wwtp	76.29	75.55	322	65.17	49.58	1181
Ptot64	0.00	0.00	0	0.00	0.00	0
Ptot65	0.00	0.00	0	0.00	0.00	0
Ptot66	0.00	0.00	3838	0.00	0.00	4888
Ptot67	0.00	0.00	2256	0.00	0.00	2873
Ptot68	0.00	0.00	1547	0.00	0.00	1898
Ptot69	0.00	0.00	2115	0.00	0.00	2595
Ptot70	12.67	11.69	618	12.77	0.00	2225
Ptot71	43.10	42.20	813	51.41	28.34	2014
Ptot72wwtp	73.75	73.05	879	38.53	25.12	2748
Ptot73				0.00	0.00	0
Ptot74				0.00	0.00	0
Ptot75				0.00	0.00	5592
Ptot76				0.00	0.00	3287
Ptot77				0.00	0.00	6796
Ptot78				0.00	0.00	9292
Ptot79				0.00	0.00	4209
Ptot80				26.08	18.53	2972
Ptot81wwtp				0.00	0.00	2359

Note: InitEM are the initial emissions of P. Ptot is the reduction percentages of total P.

Table AI.3 Total required nitrogen emission reduction through measures.

	Elbe			Rhine		
	Without wet-lands [%]	With wet-lands [%]	InitEM [tonnes N]	Without wet-lands [%]	With wet-lands [%]	InitEM [tonnes N]
Nmeas01	0.00	0.00	215	0.00	0.00	70
Nmeas02	36.06	36.02	112	39.12	36.58	37
Nmeas03	62.41	61.85	13923	95.10	69.34	2749
Nmeas04	79.76	76.91	27222	84.60	84.60	5375
Nmeas05	28.25	28.06	4531	41.67	30.55	10694
Nmeas06	22.85	22.55	6001	44.02	26.49	14164
Nmeas07	6.48	5.88	1872	25.41	2.40	2419
Nmeas08	31.65	30.99	3471	61.14	31.51	2718
Nmeas09wwtp	0.00	0.00	4388	39.09	0.00	8617
Nmeas10	0.00	0.00	407	0.00	0.00	99
Nmeas11	36.06	36.02	213	39.50	36.73	52
Nmeas12	62.41	61.85	28361	95.10	71.42	8400
Nmeas13	79.76	76.91	55452	84.60	84.60	16424
Nmeas14	28.25	28.06	8593	43.28	31.25	14177
Nmeas15	22.85	22.55	11381	46.56	27.58	18777
Nmeas16	6.48	5.88	3550	29.81	4.83	3038
Nmeas17	31.65	30.99	6583	66.20	34.06	3689
Nmeas18wwtp	0.00	0.00	8323	48.53	0.00	9211
Nmeas19	0.00	0.00	118	0.00	0.00	53
Nmeas20	36.06	36.02	62	38.15	36.18	28
Nmeas21	62.41	61.85	9282	90.17	63.97	19275
Nmeas22	79.76	76.91	18148	84.60	84.60	37687
Nmeas23	28.25	28.06	2500	37.49	28.77	11063
Nmeas24	22.85	22.55	3311	37.43	23.67	14652
Nmeas25	6.48	5.88	1033	16.24	0.00	1063
Nmeas26	31.65	30.99	1915	49.63	26.37	1144
Nmeas27wwtp	0.00	0.00	2421	33.57	0.00	10619
Nmeas28	0.00	0.00	12	0.00	0.00	52
Nmeas29	36.02	35.98	6	38.07	36.14	27
Nmeas30	61.90	61.35	28103	89.05	63.50	15539
Nmeas31	77.17	74.40	54947	84.60	84.60	30382
Nmeas32	28.07	27.89	5927	37.12	28.61	8881
Nmeas33	22.58	22.29	7849	36.84	23.42	11763
Nmeas34	5.49	4.91	2582	15.32	0.00	1477
Nmeas35	30.74	30.11	3053	48.53	25.84	1611
Nmeas36wwtp	0.00	0.00	11019	34.00	0.00	10584
Nmeas37	0.00	0.00	8	0.00	0.00	44
Nmeas38	36.29	36.24	4	38.37	36.27	23
Nmeas39	65.44	64.77	18595	92.95	65.17	11296
Nmeas40	84.60	84.60	36357	84.60	84.60	22086
Nmeas41	29.25	29.03	5390	38.42	29.16	7584
Nmeas42	24.44	24.09	7138	38.89	24.30	10045
Nmeas43	13.24	12.49	1737	18.15	0.00	2366

	Elbe			Rhine		
	Without wetlands [%]	With wetlands [%]	InitEM [tonnes N]	Without wetlands [%]	With wetlands [%]	InitEM [tonnes N]
Nmeas44	37.65	36.85	1693	52.10	27.43	2232
Nmeas45wwtp	0.00	0.00	8701	35.17	0.00	11876
Nmeas46	0.00	0.00	68	0.00	0.00	54
Nmeas47	35.99	35.95	36	37.81	36.03	29
Nmeas48	61.48	60.94	16853	85.61	62.02	22948
Nmeas49	75.05	72.35	32951	84.60	77.80	44870
Nmeas50	27.93	27.75	4134	35.97	28.12	11799
Nmeas51	22.36	22.07	5475	35.03	22.64	15628
Nmeas52	4.77	4.21	1369	12.64	0.00	2987
Nmeas53	30.06	29.44	1270	45.26	24.32	4139
Nmeas54wwtp	0.00	0.00	13603	28.48	0.00	12159
Nmeas55	0.00	0.00	45	0.00	0.00	39
Nmeas56	36.20	36.15	24	38.16	36.18	20
Nmeas57	64.28	63.66	17073	90.27	64.02	9684
Nmeas58	84.60	84.60	33381	84.60	84.60	18934
Nmeas59	28.87	28.66	4533	37.52	28.78	5856
Nmeas60	23.83	23.50	6004	37.48	23.69	7756
Nmeas61	9.72	9.04	1548	16.35	0.00	1618
Nmeas62	34.69	33.96	1869	49.75	26.44	2209
Nmeas63wwtp	0.00	0.00	3338	33.21	0.00	12253
Nmeas64	0.00	0.00	47	0.00	0.00	97
Nmeas65	36.14	36.10	24	37.35	35.84	51
Nmeas66	63.51	62.91	10368	79.58	59.44	13206
Nmeas67	84.60	82.26	20273	84.60	64.86	25821
Nmeas68	28.61	28.41	7577	33.96	27.26	9297
Nmeas69	23.43	23.11	10036	31.86	21.29	12314
Nmeas70	8.33	7.69	1578	8.40	0.00	5684
Nmeas71	33.40	32.70	3215	39.84	21.96	7962
Nmeas72wwtp	0.00	0.00	9124	26.14	0.00	28512
Nmeas73				0.00	0.00	993
Nmeas74				35.55	35.08	521
Nmeas75				55.47	49.12	15108
Nmeas76				44.93	13.11	29540
Nmeas77				25.93	23.82	33291
Nmeas78				19.20	15.87	44093
Nmeas79				0.00	0.00	10753
Nmeas80				20.21	14.36	11753
Nmeas81wwtp				0.00	0.00	24470

Note: InitEM are the initial emissions of N. Nmeas is the percentage of emission reduction through measures at farms (the order of regions in Table 2.1 is followed for the Elbe and the order of regions in Table 2.3 is followed for the Rhine, the order of sectors is given in Equation (5.13)).

Table AI.4 Total required nitrogen and phosphorus emission reduction through quota restrictions at farms and measures at wastewater treatment plants.

	Elbe			Rhine		
	Without wetlands [%]	With wetlands [%]	InitEM [tonnes N or P]	Without wetlands [%]	With wetlands [%]	InitEM [tonnes N or P]
Nquota01	4.19	4.06	215	13.56	5.80	70
Nquota02	0.98	0.94	112	3.16	1.35	37
Nquota03	0.00	0.00	13923	0.00	0.00	2749
Nquota04	0.00	0.00	27222	0.00	0.00	5375
Nquota05	0.00	0.00	4531	0.00	0.00	10694
Nquota06	0.00	0.00	6001	0.00	0.00	14164
Nquota07	0.00	0.00	1872	0.00	0.00	2419
Nquota08	0.00	0.00	3471	0.00	0.00	2718
Pwwtp09	71.19	70.54	423	51.71	37.23	831
Nquota10	4.19	4.06	407	14.68	6.28	99
Nquota11	0.98	0.94	213	3.42	1.46	52
Nquota12	0.00	0.00	28361	0.00	0.00	8400
Nquota13	0.00	0.00	55452	0.00	0.00	16424
Nquota14	0.00	0.00	8593	0.00	0.00	14177
Nquota15	0.00	0.00	11381	0.00	0.00	18777
Nquota16	0.00	0.00	3550	0.00	0.00	3038
Nquota17	0.00	0.00	6583	0.00	0.00	3689
Pwwtp18	71.19	70.54	802	85.70	75.88	888
Nquota19	4.19	4.06	118	10.64	4.55	53
Nquota20	0.98	0.94	62	2.48	1.06	28
Nquota21	0.00	0.00	9282	0.00	0.00	19275
Nquota22	0.00	0.00	18148	0.00	0.00	37687
Nquota23	0.00	0.00	2500	0.00	0.00	11063
Nquota24	0.00	0.00	3311	0.00	0.00	14652
Nquota25	0.00	0.00	1033	0.00	0.00	1063
Nquota26	0.00	0.00	1915	0.00	0.00	1144
Pwwtp27	71.19	70.54	233	71.69	55.56	1024
Nquota28	4.07	3.94	12	10.38	4.44	52
Nquota29	0.95	0.92	6	2.42	1.03	27
Nquota30	0.00	0.00	28103	0.00	0.00	15539
Nquota31	0.00	0.00	54947	0.00	0.00	30382
Nquota32	0.00	0.00	5927	0.00	0.00	8881
Nquota33	0.00	0.00	7849	0.00	0.00	11763
Nquota34	0.00	0.00	2582	0.00	0.00	1477
Nquota35	0.00	0.00	3053	0.00	0.00	1611
Pwwtp36	68.62	68.01	1062	68.20	52.36	1020
Nquota37	4.89	4.74	8	11.29	4.83	44
Nquota38	1.14	1.10	4	2.63	1.12	23
Nquota39	0.00	0.00	18595	0.00	0.00	11296
Nquota40	0.00	0.00	36357	0.00	0.00	22086
Nquota41	0.00	0.00	5390	0.00	0.00	7584

	Elbe			Rhine		
	Without wetlands [%]	With wetlands [%]	InitEM [tonnes N or P]	Without wetlands [%]	With wetlands [%]	InitEM [tonnes N or P]
Nquota42	0.00	0.00	7138	0.00	0.00	10045
Nquota43	0.00	0.00	1737	0.00	0.00	2366
Nquota44	0.00	0.00	1693	0.00	0.00	2232
Pwwtp45	84.63	83.73	839	65.08	49.50	1145
Nquota46	3.97	3.85	68	9.58	4.10	54
Nquota47	0.92	0.90	36	2.23	0.95	29
Nquota48	0.00	0.00	16853	0.00	0.00	22948
Nquota49	0.00	0.00	32951	0.00	0.00	44870
Nquota50	0.00	0.00	4134	0.00	0.00	11799
Nquota51	0.00	0.00	5475	0.00	0.00	15628
Nquota52	0.00	0.00	1369	0.00	0.00	2987
Nquota53	0.00	0.00	1270	0.00	0.00	4139
Pwwtp54	67.33	66.75	1311	56.26	41.41	1172
Nquota55	4.63	4.48	45	10.66	4.56	39
Nquota56	1.08	1.04	24	2.48	1.06	20
Nquota57	0.00	0.00	17073	0.00	0.00	9684
Nquota58	0.00	0.00	33381	0.00	0.00	18934
Nquota59	0.00	0.00	4533	0.00	0.00	5856
Nquota60	0.00	0.00	6004	0.00	0.00	7756
Nquota61	0.00	0.00	1548	0.00	0.00	1618
Nquota62	0.00	0.00	1869	0.00	0.00	2209
Pwwtp63	76.29	75.55	322	65.17	49.58	1181
Nquota64	4.45	4.31	47	8.18	3.50	97
Nquota65	1.04	1.00	24	1.90	0.81	51
Nquota66	0.00	0.00	10368	0.00	0.00	13206
Nquota67	0.00	0.00	20273	0.00	0.00	25821
Nquota68	0.00	0.00	7577	0.00	0.00	9297
Nquota69	0.00	0.00	10036	0.00	0.00	12314
Nquota70	0.00	0.00	1578	0.00	0.00	5684
Nquota71	0.00	0.00	3215	0.00	0.00	7962
Pwwtp72	73.75	73.05	879	38.53	25.12	2748
Nquota73				2.58	1.10	993
Nquota74				0.60	0.26	521
Nquota75				0.00	0.00	15108
Nquota76				0.00	0.00	29540
Nquota77				0.00	0.00	33291
Nquota78				0.00	0.00	44093
Nquota79				0.00	0.00	10753
Nquota80				0.00	0.00	11753
Pwwtp81				0.00	0.00	2359

Note: InitEM are the initial emissions of N and P. Nquota is the percentage of N reduction through quota restrictions on farms. Pwwtp is the percentage of P reduction at wastewater treatment plants.